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FROM AIR TO MUSIC

Acoustical, Physiological and Perceptual Aspects of Reed Wind Instrument Playing and Vocal-Ventricular Fold Phonation

av

Leonardo Fuks

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An ancestral and recurrent dream of humankind is that of flying.
In my ordinary flying dreams,
whenever I inhale, I start levitating in the space;
when I exhale, I immediately return to the firm ground.

Playing a wind instrument may follow the same simple, supernatural rule:
in blowing, one donates life and sound to other beings,
and gains the Earth;
in inspiring, one must incorporate spirits and angels.

To the memory of my father and my grandparents

Um sonho ancestral e recorrente da humanidade é o de voar.
Em meus ordinários sonhos voadores
sempre que inalo, começo a levitar
e quando exalo, imediatamente volto ao chão firme

Tocar um instrumento de sopro deve seguir a mesma regra simples e
sobrenatural:
ao soprar, doamos vida e som aos outros seres, e ganhamos a Terra;
ao inspirar, devemos incorporar espíritos e anjos

à memória de meu pai e de meus avós

Abstract

This thesis presents an interdisciplinary research on reed woodwind instruments and human voice, focusing on acoustical, physiological and perceptual aspects of sound generation.

The wind instruments studies concentrate on breathing and blowing under realistic conditions and provide a deeper insight on required aerodynamical input parameters. The variation of blowing pressure with loudness and fundamental frequency was measured in professional players of oboe, bassoon, clarinet, and alto saxophone and was found to be quite systematic, though differing between the instruments. Airflow for sustained tones was measured by indirect spirometry, together with blowing pressure and sound pressure level, using extreme reeds, one soft and one hard. Recordings were made in an ordinary room as well as in a calibrated reverberant chamber. Also, tones with an intense vibrato were analysed for the oboe, the saxophone and the bassoon. The results revealed wide variations in blowing pressure, suggesting that a rhythmic modulation of the contraction of expiratory muscles was a main factor, and relatively small variation in fundamental frequency. The players' perception of self-produced static lung pressures typically used in performances was analysed in a psychophysical experiment, that revealed a quasi-linear relationship between perceived and produced pressures. The respiratory movements during playing were measured by a non-invasive technique, respiratory inductive pletysmography, which offered acceptably reliable data. The results revealed significant participation of the rib cage in all players and also of the abdominal wall in several players. Also, the impact of the continuous changes of O_2 and CO_2 gases in the pulmonary air exhaled during performance on the fundamental frequency was predicted from theory and compared with experimental data. The effect, smaller than that of temperature variation, still would represent a factor of potential relevance to wind instrument intonation. In addition, the sound production characteristics of a particular type of phonation, perceptually judged as similar to that used in Tibetan chant, were studied by high-speed imaging. Also, it was examined using acoustical and physiological methods. The results revealed a synchronised co-oscillation of the vocal and ventricular folds, which yields a lowering of fundamental frequency due to multiplication of the vocal fold period.

Keywords: blowing pressures, reed woodwinds, oboe, clarinet, saxophone, bassoon, music performance, respiratory inductive plethysmography, perception of blowing pressure, intonation, aerodynamics, Tibetan chant, ventricular folds, respiratory behaviour, airflow, vibrato, music acoustics, physiology of music.

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1. Included papers

The present dissertation comprises a summary and the following papers, listed in systematic order.

Paper I	Leonardo Fuks & Johan Sundberg (1996): **“Blowing pressures in reed woodwind instruments”**, *KTH TMH-*QPSR 3/1996, 41-57, Stockholm, to appear in a revised and modified version as “Blowing pressures in bassoon, clarinet, oboe and saxophone”, in press for *Acustica/acta acustica*.
Paper II	Leonardo Fuks (1998): **“Aerodynamic input parameters and sounding properties in naturally blown reed woodwinds”**, *KTH TMH-QPSR* 4/1998, 1-11, Stockholm
Paper IIIa	Leonardo Fuks (1996): **“Prediction of pitch effects from measured CO_2 content variations in wind instrument playing”**, *KTH TMH-QPSR* 4/1996, 37-43, Stockholm
Paper IIIb	Leonardo Fuks (1997): **“Prediction and measurements of exhaled air effects in the pitch of wind instruments”**, *Proceedings of the Institute of Acoustics*, ISMA'97 Conference, Edinburgh, Vol. 19: Part 5 (1997), Book 2, 373-378
Paper IV	Leonardo Fuks & Johan Sundberg (1998): **“Respiratory inductive plethysmography measurements on professional reed woodwind instrument players”**, *KTH TMH-QPSR* 1-2/1998, 19-42, to appear in a revised and modified version as "Using Respiratory Inductive Plethysmography for Monitoring Professional Reed Instrument Performance"; in press for *Medical Problems of Performing Artists,* March 1999
Paper V	Leonardo Fuks (1998): **“Assessment of blowing pressure perception in reed wind instrument players”**, *KTH TMH-QPSR* 3/1998, 35-48, Stockholm, submitted for publication
Paper VI	Leonardo Fuks, Britta Hammarberg & Johan Sundberg (1998): **“A self-sustained vocal-ventricular phonation mode: acoustical, aerodynamic and glottographic evidences”**, *KTH TMH-QPSR* 3/1998, 49-59, Stockholm

The papers will be henceforth referred to by their Roman numerals. Figures and Tables will be referred to by the same way as they appear in their respective papers.

2. List of Abbreviations and Conventions

Note name convention:	the real note names, rather than the transposed ones are adopted throughout the thesis. For example, in the alto saxophone, A_4 stands for the standard A 440 Hz, rather than C_4 as it would sound from a score.
ΔP_{mouth}	amplitude of mouth pressure variations during vibrato
AW	abdominal wall
c	velocity of sound
EGG	electroglottogram
ERV	expiratory reserve volume
FG	flow-glottogram
FRC	functional residual capacity
IC	inspiratory capacity
I_{rev}	sound intensity as estimated in the reverberant chamber
IVM	isovolume manoeuvre
jnd	just noticeable difference
p_0 , P_{mouth} or P_m	pressure in the mouth, blowing pressure
PFE	power function exponent
RC	rib cage
REL	resting end-expiratory level
RIP	respiratory inductive pletysmography
RV	residual volume
SPL	sound pressure level
TLC	total lung capacity
T_r	reverberation time
$\dot{V}$	airflow through the reed/mouthpiece
VC	vital capacity
V_t	tidal volume
VVM	vocal-ventricular (phonation) mode

3. Introduction

Respiration and **breathing** are keywords in this thesis, since they play a central role in wind instrument playing as well as in voice production. In wind instrument playing and in singing the performer shares the vital metabolic air with the sound-producing organ. In a more general perspective, respiratory pauses and sometimes even respiratory sounds contribute significantly to music performance, also in the case of some non-wind instruments. For instance, in the playing of bowed string instruments, western classical performers frequently employ the sounds and gestures of respiration to enhance expressiveness and also to mark musical phrases. Thus, breathing and the associated pauses serve as structural elements in musical performance, often possessing a significant esthetical content.

This study comprises a suite of papers conceived with the intention to examine the theme under an interdisciplinary perspective, including musical, acoustical, perceptual and physiological aspects. It is concentrated on the mechanical-reed woodwinds, henceforth reed woodwinds, which comprise the oboe, clarinet, saxophone and bassoon. This interdisciplinary approach is justified by the assumption that it is not possible to fully understand the process of playing a wind instrument if any of these aspects is overlooked in the analysis. Figure 1 shows a schematic representation of the breathing behaviour in wind instrument playing.

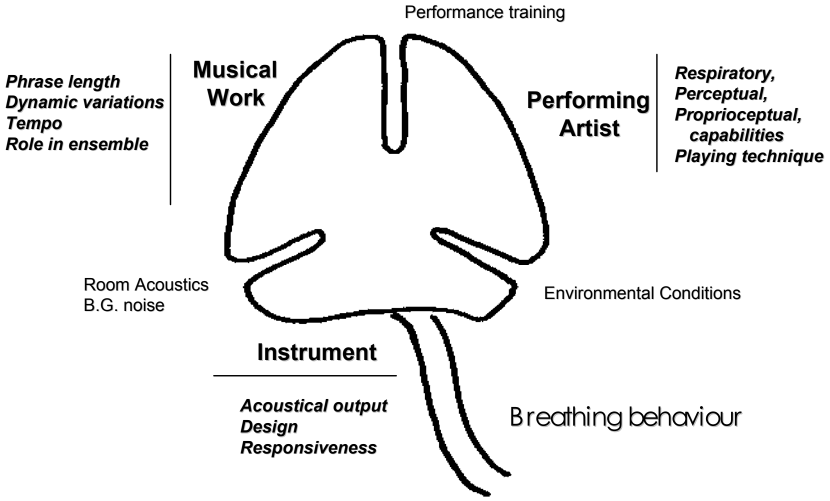


Figure 1. Illustration, in the form of a trefoil diagram, of the phenomenon of breathing behaviour in wind instrument playing. As shown, breathing needs to accommodate demands originating from three main systems: performer, instrument and musical work.

As schematically illustrated in Figure 1, breathing behaviour in wind instrument playing is influenced by a great number of different factors, each raising demands on the player's performance. The structural organisation of the music imposes certain requirements regarding tempo, phrase length, dynamic variation, and the musical role in the ensemble. The performing artist has to accommodate these demands within the constraints and potentials of his own physiological system, including respiratory, perceptual, and proprioceptual capabilities. The instrument consumes air, provided by the player's metabolic system. It consumes air to an extent that depends on many factors, such as the desired acoustical output, the technique of playing, and the responsiveness of the instrument. The task of the musician is to harmonise all these factors so as to reach a satisfactory artistic end result. Many of these factors have been neglected in previous investigation of wind instruments. Conversely, some research in the area of respiration may profit from improved information about breathing characteristics of wind instrumentalists. Likewise, the understanding of the function of wind instruments, as well as of the musical work and its performance, may gain from information about the physiology of the player. In addition, the knowledge gathered and produced in this thesis may have applications in the development of new playing techniques, the designing and improving of instruments, in compositional work, as well as in the development of computer algorithms for artificial instruments. From a wider perspective, the thesis can be regarded as a meeting point of several disciplines, such as musical acoustics, instrument making, music theory, physiology, ergonomics, and instrumental practice.

4. Previous work

4a Physiological Aspects of Music Performance

Early interest in how players behave in order to operate wind instruments dates at least from the last century (Stone, 1874; Barton & Laws, 1902). Most of those studies were produced by physiologists who were mainly interested in the supposedly extreme levels of effort required, their physiological effects on circulation and respiration and on possible association to respiratory diseases (Frucht, 1937; Roos, 1936, 1938, 1940; Faulkner & Sharpey-Schafer, 1959; Singer, 1960; Akgun & Ozgonul, 1967; Watson, 1972; Gibson, 1979; Schorr-Lesnick et al., 1985; Gilbert, 1998). Part of this literature refers to pulmonary emphysema, a chronic pulmonary disease (Becker, 1911; Hävermark & Lundgren, 1957; Rejsek et al.; 1961). In this disease, there is an abnormal enlargement of the air spaces distal to the terminal bronchioles, accompanied by destruction of their walls (Snider, 1994). Yet, the claim that the playing of wind instrument might predispose to the development of pulmonary emphysema has never been confirmed (Bouhuys, 1964; Lucia, 1994). Rather, emphysema has been proved to be connected to smoking habits, to chronical respiratory disease and to genetically-related disposition (Snider, 1994). On the other hand, patients with respiratory problems who have music as an occupation are more likely to experience symptoms triggered by the demands imposed by performance. Similarly, wind players will tend to notice more clearly the physiological modifications associated with aging.

Arend Bouhuys probably contributed most importantly to the present knowledge on physiology of wind instrument playing. He studied pressure, airflow, sound power, efficiency, CO_2 variations, heart rates, and other aspects (Bouhuys, 1964, 1965, 1968). Using a pneumograph he assessed qualitatively lung volume variations and also discussed some respiratory techniques, such as circular breathing (Bouhuys, 1964).

Based on the fact that blowing pressure in the observed brass instruments presented wider ranges than in woodwinds, Bouhuys hypothesised that mouth pressure control would be more important for those instruments than in any other type of winds. It must be borne in mind, however, that in brass instruments, where the lips serve as the oscillating reeds, the lip tension control is as important as the expiratory pressure. In woodwind, the embouchure, i. e. the link between the player's mouth and the instrument (see below), is also very relevant, although it does not affect the pitch to the same critical extent as in brass instruments.

Other contributions to the physiology of wind instrument playing were given by Navrátil & Rejsek (1968), Vivona (1968), Benade (1986), among others.

4b Music Acoustics

Wind instruments have been intensely investigated in the domain of music acoustics. From the pioneering contributions of Weber (ca. 1830, as quoted by Bouasse, 1929) and Helmholtz (1863), followed by the important work of Bouasse (1929), the physics of wind instruments has attracted the attention of several generations of investigators.

With regard to reed woodwinds, particularly significant contributions were offered by Meyer (1961), Backus (1961, 1963a, 1963b, 1977), Benade (1968, 1976, 1986, 1988), Nederveen (1969), Worman (1971), Bak (1978), Plitnik & Strong (1979), Thompson (1979), Stewart & Strong (1980), Schumacher (1981), McIntyre et al. (1983), Pawlosky & Zoltowsky (1985, 1987), Gilbert (1986, 1989, 1991), Meynial (1987), Sommerfeldt & Strong (1988), Gibiat (1990), Hirschberg et al. (1990), Keefe (1990), Idogawa et al. (1993), and others.

A majority of the studies of reed instruments concern the acoustics of the clarinet, a quasi-cylindrical tube resonator excited by a simple-reed oscillator. The large concentration of studies on this instrument is probably due to the fact that the instrument possesses characteristics that are favourable from the point of view of experimental research. For example, the amplitude of vibration may be relatively small and the reed does not necessarily beat against the mouthpiece. This and the quasi-constant cross-sectional area of the tube resonator reduce complexity, particularly as compared to double reeds attached to conical tubes. In addition, the clarinet is a widespread and reasonably low-priced instrument, homogeneous in terms of design and used in many types of ensembles and styles.

The combined theoretical and experimental knowledge provided by the above-mentioned and other studies, permits simulation and prediction of instrument behaviour, at least under specific circumstances. However, many problems need still to be solved before the full system can be exhaustively described. The instruments are geometrically complex with a multitude of tonehole configurations, the reeds are neither standard, nor homogeneous, and the player's behaviour cannot be assumed to be constant and absolutely reproducible. In addition, music requires quite fast and complex changes of the output sound. All this causes difficulties in defining parameters and initial conditions of a system of equations intended to describe, at least hypothetically, the phenomena involved. Fletcher & Rossing (1998) point out that an accurate prediction of the airflow through a wind instrument, that takes into account the effect of viscosity, necessarily requires the solution of the Navier-Stokes equations (e.g. see Yih, 1969). These are non-linear and would demand numerical methods for their solution, once the system is suitably defined.

4c Musical Pedagogy

Many pedagogical text-books for wind instruments, sometimes called "methods", often considers techniques for respiration and breathing for sound production (Quantz, 1752; Rockstro, 1890; Palmer, 1952; Rothwell, 1953, 1976; Thurston, 1956; Spencer, 1958; Stein, 1958; Sprenkle & Ledet, 1961; Bonade, 1962; Teal, 1963; Timm, 1964; Putnik, 1970; Goossens, 1977; Weait, 1979; Mazzeo, 1981; Mauk, 1986; Rehfeldt, 1994). In some cases, these sections review some basic anatomy of the respiratory apparatus, sometimes complemented by descriptions of the inspiratory and expiratory muscles, recommendations on posture during playing and on optimum inhalation strategy and instructions on how to achieve "support" and "use the diaphragm". Unfortunately, these two latter terms seem vague and used in diverging meanings among different authors. In addition, differing meanings of the same term are often used in different fields. Obviously, this lack of consensus regarding the meaning of terms will cause misunderstandings and confusion among students and colleagues.

Occasionally there is a marked discrepancy between the contents found in musical text-books and the current knowledge in respiratory physiology and mechanics; sometimes totally neglected are the great advances, achieved particularly after the end of WWII (see e.g., Rahn, 1946; Agostoni 1964, 1965, 1967; Wade, 1954; Konno and Mead, 1967, 1968; for a broad and detailed account of respiration, see Roussos, 1995). This obviously hampers interdisciplinary communication.

A professional brass instrument player and teacher, Arnold Jacobs (1915-1998), in particular, has paid major attention to respiratory aspects. Jacobs was probably the most influential wind instrument teacher in the USA and other countries, particularly among brass players. His pedagogical activities were exclusively oral, through private lessons and workshops (Stewart, 1987; Frederiksen, 1996). In his lessons, Jacobs used an ensemble of devices, developed for respiratory clinical purposes, providing visual feedback to the students regarding pulmonary pressure, air flow and lung volume. Also, he designed or adapted some equipment aiming at stimulating respiratory function in players and at increasing the degree of consciousness and training regarding muscular control. Interestingly, Jacobs used a terminology that was more pedagogically-oriented than based on physical facts. For instance, he emphasises "flow" as a keyword for playing control, as opposed to "pressure", which he deemed a negative term. This seems to be due to the psychological effect of these words. Different terms may tend to trigger different behaviours in players. Probably he did not overlook the fact that reed wind instruments and brass instruments are generally regarded as pressure-controlled systems (Benade & Gans, 1968; Elliot & Bowsher, 1982). There is also another reason for emphasising "flow". In brass instruments there is a wide range of combinations of mouth pressure and lip resistance that produce the same output level. If the player is able to use configurations requiring lower pressures, i.e., lower embouchure resistance and/or stiffness, the airflow should be maximised and the playing effort reduced (Nederveen, 1969). These general principles are likely to apply also to woodwind instruments, at least to some extent.

Music acoustics research would have the potential of contributing importantly to music pedagogy and performance. Definitions of terms based on scientific data should be easier to accept than definitions derived from experts' introspection. Likewise, realistic ideas of anatomy and physiology have a great potential to gain wide acceptance, thus promoting interdisciplinary exchange.

5. Instruments analysed

This investigation was focused on reed woodwind instruments and on voice, the latter with respect to a particular effect of vocal-ventricular phonation. Limiting the instrumental study to four types of instruments was due to practical and methodological considerations. A practical consideration was the huge amount of experiments and data processing required to achieve some degree of depth in the analysis of a given instrument. A methodological consideration was the vast differences in the principles that regulate the sound generation in different types of wind instruments, e.g., the above-mentioned mechanical reed, free reed (harmonica, accordion), air-reed (flutes, recorders, etc.) and lip-reed (brass) instruments. These differences lead to separate playing techniques, necessitating the use of different theoretical approaches for each instrument type. Nevertheless, most of the studies and procedures in this work might be useful in future investigations of other types of wind instruments.

The idea to include the human voice in this work originated from the observation of some apparent similarities between the mechanical system of reed instruments and certain properties of the specific phonation mode studied. These similarities will be explained in greater detail below.

5a Reed woodwinds

Mechanical reed woodwinds constitute an important group of wind instruments, which in western classical tradition includes oboes, clarinets, saxophones and bassoons. In these instruments, the function of the reed is to modulate the airstream that enters the air-column of the instrument, exciting and maintaining the vibrations in the bore.

Figure 2. Bassoon plant. Despite standard and accurate manufacturing procedures adopted by the maker, the different parts of an instrument must be mutually adjusted, so that equivalent parts are not usually interchangeable. The instruments shown incorporate the German Heckel system (Blei & Baumann, 1987).

Each of the instruments are available in two or more "voices", according to pitch range: soprano oboe, oboe d'amore, English horn; soprano clarinet (in Bb and in A), Eb clarinet, basset horn, bass clarinet; soprano, alto, tenor, bass saxophones; bassoon and contra-bassoon. There are still more variants. Usually, different voices of an instrument use almost identical fingerings. There are, however, instruments designed with different key systems and tonehole configurations, particularly for the oboe and the bassoon, which may also differ in sound quality and in playability, see Figure 2.

Among the four instrument types, we selected the four most commonly used, shown in Figures 3-6. The double reeds are shown in greater scale together with the instruments. The reeds for the alto soprano and the clarinet are very similar, the first being larger in all dimensions, see Figure 7. The reeds for all four instruments are generally made of a species of bamboo, *Arundo donax*. Other, mainly synthetic, materials are also available. However, the bamboo is by large the most common among professional classical users. Since oboe and bassoon reeds are autonomous pieces, directly attached to the instrument bore, they will be referred to as reeds or mouthpieces. Figures 3 to 7 from Nederveen (1969).

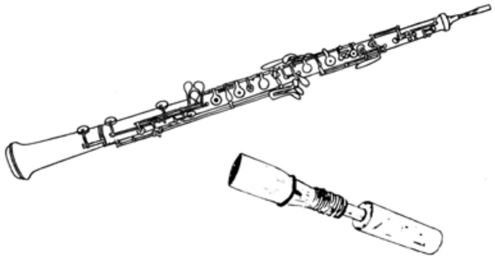


Figure 3. Soprano oboe

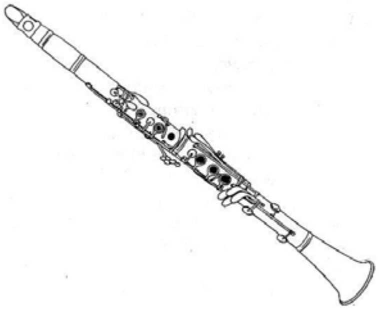


Figure 4. Soprano clarinet

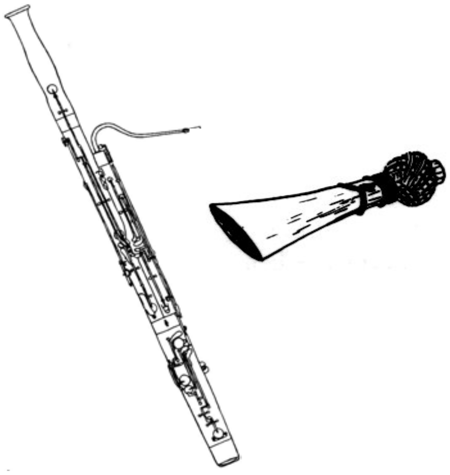


Figure 5. Bassoon

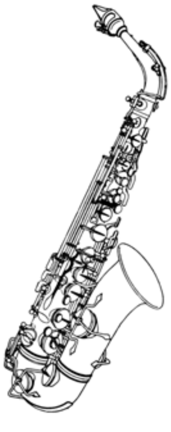


Figure 6. Alto-saxophone

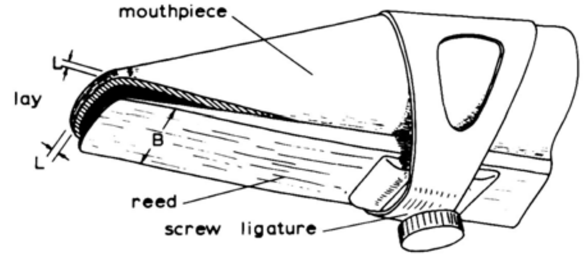


Figure 7. A clarinet/saxophone mouthpiece. The reed is rigidly clamped by the ligature in one extreme. The blade is free to oscillate along the curved profile of the mouthpiece. The airflow slit is the varying opening area between the reed margins and the mouthpiece lay. Embouchure sets a different contact region between the parts, moved towards the tip, characterised by a less rigid and more damped attachment (see Figures 10a and b).

Reed woodwind instruments produce tones at pitches which are dependent on many factors: the length of the acoustical air-column inside the instrument, the shape of the instrument bore, the sound speed of the air inside the instrument, the natural vibrating frequencies of the reeds and, to some extent, the blowing pressure. Also, the so-called embouchure is highly influential. The term embouchure is somewhat vague (Porter, 1967; 1973). In this thesis it is assumed to be the constellation of forces and positions in the lips, mouth region and face that act on the instrument. A more detailed account for the effects of the embouchure is given in the end of this section.

The length of the air-column is mainly determined by the fingering applied to the instrument mechanism, which permits a large combination of open and closed tone-holes. This length can be modified by the longitudinal position of the mouthpiece, which allows fine tuning adjustment of the instrument with respect to an intonation reference. The tuning is also affected by the acoustical length of the reed, which depends on the physical reed length and shape.

The shape of the instruments' bore may be roughly approximated to a cylinder in the clarinet and to a truncated cone in the oboe, saxophone and bassoon. In simplified terms, the sound waves travelling in a cylindrical tube closed at one end, such as in an idealised clarinet, may be considered as quasi plane. The frequencies of the resonance modes approach a harmonic series containing the odd multiples of the lowest resonance. For a conical tube, the waves produced are quasi spherical, thus a series comprising all multiples of the lowest resonance frequency. In reality, those resonance modes present inharmonicities, i.e. they are not exact integer multiples of the lowest resonance (Bouasse, 1929; Benade, 1968; Gilbert, 1991).

The speed of sound propagation in the instrument is of great importance. The reason is that the reed oscillations are controlled by a vibratory regime in the bore; acoustic pulses, created by the reed’s modulation of the airstream from the mouth, travel along the bore, are reflected at the effective end point of the air-column and return back to the reed chamber. The travel time depends on the length of the bore and of the sound speed. This speed depends on the temperature, humidity and the composition of the gas inside the instrument, which thus affect the fundamental frequency of the tones, see Figure 8. The magnitude of these effects is investigated in detail in Papers IIIa and IIIb.

Figure 8. Players must adapt themselves to perform under various conditions. At low temperatures, the normal fundamental pitch of a wind instrument should decrease considerably, for example, almost a semitone at -10°C. However, as the instruments are warmed up, this deviation should be greatly reduced. Photo by Blei & Baumann (1987).

The reeds generally oscillate at frequencies that are far below their inherent frequencies, i.e. frequencies at which they would vibrate should they not be coupled to an air-column (Helmholtz, 1863; Bouasse, 1929; Benade, 1976). For instance, when the player increases the load forces in the embouchure, thus increasing the reed stiffness, the inherent frequency of the reed is raised. This increases to some extent the sounding pitch. Players continuously use this principle for fine adjustments of intonation. Also, in clarinets and saxophones the single reed is bent against the curved lay of the mouthpiece, see Figure 7. This implies an increase in load force and a shortening in the vibrating length of the reed, which raises the fundamental frequency to some degree. This affects the equivalent length of the instrument (Gilbert, 1991, and see below). "Squeak" sounds, high-pitched sounds that accidentally occur mainly in the clarinet, are explained as a consequence of an insufficient coupling of the reed to the air-column modes. In this case, the reed vibrates closer to its natural frequency, occasionally reinforced and assisted by a resonant peak of the mouth cavity and/or the instrument bore. "Squeak" sounds are sometimes used in contemporary music, often controlled by the direct contact of the teeth on the reed (Rehfeldt, 1994) and/or by skilful shaping of the vocal tract.

Apart from the embouchure’s effect on reed stiffness, it probably also adds to its effective mass. The surface of the lips that touches the reed should form a layer of tissue that participates in the oscillations. This should reduce the natural frequency of the reed, implying that the fundamental frequency should decrease somewhat. This seems to be a neglected factor in previous investigations. In a pilot experiment, we applied a thin film of plastic gum of 0.1 g on both sides of a bagpipe reed, connected to its air-column (a conical *chanter*), blowing at constant pressure. This caused the fundamental frequency to decrease by more than 15 cents. The bagpipe reed is located inside a cap, isolating it from the lips. This result suggests that the mass added to the reed by the lips is significant.

Blowing pressure is intimately related to airflow in reed woodwinds. Analysis of the static airflow, void of oscillation, across a reed-like device has shown characteristic relations between the two, see Figure 9 (from Fletcher and Rossing, 1998, after Wijnands & Hischberg, 1995 and Worman, 1971). They reveal that, for a given embouchure, airflow varies with pressure according to a bell shaped curve. Acoustical and aerodynamical considerations show that self sustained oscillations will only be possible on the descending side of the curve and that these oscillations can be started at a threshold pressure, i.e., approximately one third of the pressure that completely closes the reed. The pressure-flow curves are different for double reeds, such as oboes and bassoons, although similar principles apply. The differences consist of the fact that in curve III there is hysteresis, implying that an increase of the upstream pressure to a maximum will suddenly interrupt the flow, while a different behaviour occurs when going the reverse direction.

In practical terms, the static flow curves show that for a fixed embouchure the airflow and the sound power radiated by the instrument should decrease with increasing blowing pressure. Papers I and II investigate the pressure and airflow in naturally played instruments.

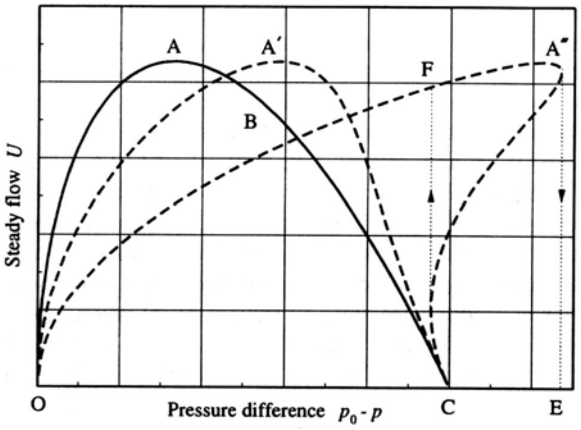


Figure 9. Pressure-flow curves through a static reed, i.e. without oscillations. With a blowing pressure of p_0 and an internal pressure of p, flow increases from O until it reaches a maximum at A and decreases until the closure point C. For the two curves on the left, the instruments can only operate in the descending part of the bell-shaped curves. Filled line represents the typical case of the clarinet (Worman, 1971). Double reeds may behave according to one of the three curves, because of internal flow resistance. From Fletcher & Rossing (1998), after Wijnads & Hirschberg (1995).

Another important phenomenon occurring in instruments is overblowing. In reed woodwinds it refers to the situation that the reed vibration frequency is controlled by a higher oscillation mode of the air column. Overblowing is caused by a particular combination of embouchure and input parameters, sometimes assisted by a special fingering. As mentioned above, conical bores have modes at approximately integer multiples of the frequency of the lowest mode. Thus, overblowing will make the reed oscillate at higher resonance modes in the air-column. Similarly, in conical bores overblowing establish reed vibrations at frequencies which are about 3, 5, 7 etc. times the lowest mode. The overblowing phenomenon delimits the different registers of the instrument. Generally, the reed instruments use no more than three registers but under special circumstances, additional registers may occur.

The oboe, Figure 3, has a length of approximately 644 mm, including the reed, and its usual range is Bb_3-G_6. The first register is limited by the note C_5. The second runs up to C_6, and has fingerings very similar to those in the first register. The fingerings in the third register are less systematic for reasons of tuning. The double reed, consisting of two opposed, curved blades tied to a metal staple, is shown in more detail in the same figure. Of paramount importance is the design and finishing of the reed scrape, as it affects the playing properties of the reed. Usually, oboe and bassoon players make and adjust their reeds according to the instruments, the material properties, and to personal preference.

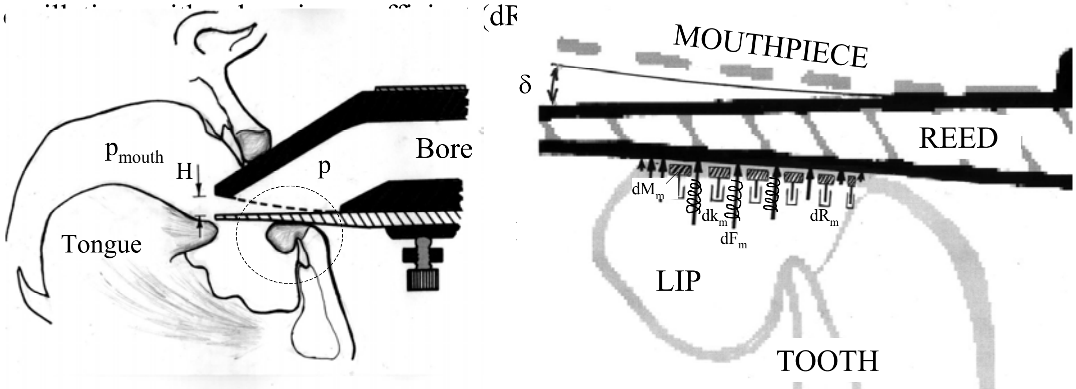
The Bb clarinet, Figure 4, has a bore measuring about 664mm and is approximately cylindrical. The instrument typically ranges between D_3 and B_6. Ab_4 limits the first register. Because its air-column modes are odd multiples of the fundamental mode, the second register gives three times the fundamental frequency, in musical terms a *duodecim* or a twelfth. This register is available from A_4, which uses the fingering of D_3 plus the register hole. This register continues up to Bb_5 (position corresponding to Eb_4). From this point on, the third register follows until B_6, with non-sequential fingerings as in the former registers. Only Boehm system clarinets, the most widespread, were used in our experiments.

The bassoon, Figure 5, like the oboe, consists of a conical tube with a double reed, measuring approximately 2560 mm and ranges typically between Bb_1 and D_5. The first register spans from Bb_1 to F_3. This is considerably larger than the other instruments. From $F\#_3$ up to D_4, the fingerings are similar to the previous octave, with the assistance of some keys. Then, the last octave comprises fingerings that vary greatly. In our experiments, all bassoons belonged to the German (Heckel) system, see Figures 2 and 5.

The alto saxophone, Figure 6, consists of a quasi-conical bore of 1062 mm and a typical playing range between Db_3 to A_5. The first register reaches E_4, the second register covers the range F_4 to A_5, and uses fingerings similar to those used in the first register. For saxophones, mostly one single system is used.

Embouchure

From the above, it is evident that the embouchure serves many different purposes, all controlled by the player. Figure 10b presents a tentative schematic model for how the mechanical parameters of the embouchure are distributed along the reed. The lips are pressed against the reed with a load force distributed on the surface (dF_m). The tissue has a stiffness (dK_m) and a mass distribution (dM_m), and also attenuates the oscillations with a damping coefficient (dR



Figures 10a and 10b. Simplified representation of the embouchure (a) and a detail with its mechanical parameters (b) on a single reed instrument. For double reeds, obviously both blades will be in contact with the lips and the factor of the reed bending along the mouthpiece lay is not present.

The purposes of the embouchure are as follows:

a) Providing an **airtight seal between mouth and mouthpiece**. To meet this demand, the embouchure may sometimes be adapted to the blowing pressure. For instance, a pressure increase might require increase of the lip contraction so as to prevent air leakage. This may potentially affect the reed behaviour. In the oboe and bassoon, both lips are folded over the teeth, while in the clarinet and the saxophone only the lower lip usually folds over the teeth while the upper teeth are in direct contact with the mouthpiece. In addition, the upper lip is pressing anteriorly against the upper surface of the mouthpiece and laterally against its sides. Some clarinet players fold the upper lip around the teeth too, like oboe and bassoon players. This technique, called "double-lip", is argued to ensure a more relaxed, steady and balanced embouchure.

b) **Controlling the degree of damping of the reed** vibrations (Nederveen, 1969; Wilson & Beavers, 1974). This damping can be applied in different regions along the reed surface, enabling a wide variation of the timbral output tone and vibration modes. Also, it is used to inhibit undesired modes of reed vibrations (“squeaks” e.g., in clarinet and saxophone).

c) **Regulating the stiffness** of the reed by means of **load force**. This force, applied normal to the reed surface, affects the reed deflections and, in the cases of clarinet and the saxophone, also the bending of the reed along the curved mouthpiece profile, as mentioned (Nederveen, 1969; Gilbert, 1991; Stewart & Strong, 1980; Meynal, 1987). Both factors increase fundamental frequency. Gilbert (1991) measured an increase of more than 30 cents, at a constant blowing pressure, between a relaxed and a tense embouchure in a high-pitched alto-saxophone note (E_5, real note).

d) **Regulating the dimensions of the slit** through which the air passes into the instrument (Nederveen, 1969; Wilson & Beavers, 1974; Bak, 1978). This function is also carried out by means of the application of the load force, as in c. The slit, or gap, is obviously variable due to the reed oscillations. An initial static (without pressure difference across the reed) and an average dynamic gap may be determined by optical or other methods. It can be expected that the dynamic gap will be smaller than the static, since the blowing pressure would add an aerodynamic component to the loading force by the lips (Nederveen, 1969; Bak, 1978; Gilbert, 1991).

e) **Adding mass** to the reed. Because of the direct contact in the embouchure, the lips participate in the reed vibrations, thus increasing its inertia. This effect alone would decrease the natural frequency of the reed to some extent, thus producing a decrease in fundamental frequency, as mentioned.

f) **Positioning and holding the instrument** relative to the player. This refers to the degree of angular freedom provided by the embouchure, affecting the posture including the positioning of the arms and, to some extent, also the fingers. It has consequences for the internal configuration of the mouth and the tongue relative to the reed. The conformation of the players' teeth and jaws are also significant to the embouchure (Porter, 1967, 1973). Also, particularly for fingerings that require the right hand just to hold the instrument (with the thumb) and the left hand to apply unbalanced forces on the instrument, the embouchure may serve to support and stabilise the instrument. One example is the fingering for Bb_5 in the clarinet, which tends to force the mouthpiece against the upper lip. This might be called an ergonomical function of the embouchure.

By modulating the embouchure, usually accompanied by a modulation of the blowing pressure, it is possible to produce a gamut of sound effects and gestures, including the so-called "lip vibrato", briefly discussed in Paper II.

It must be stressed that the above descriptions refer to embouchure in reed woodwinds. In the case of brass instruments, where the lips serve as the main oscillator, such function must be added and the purposes represented by items b, c and d do not apply. Also, the embouchure in air-reed instruments, such as flute and recorder, require a different description.

In defining the embouchure, it is possible also to include factors that determine the intraoral configuration, such as the position of the jaw and tongue. The shape of the mouth cavity is frequently assumed to be relevant to the sound production (Benade, 1986; Thomas et al., 1988; Backus, 1963b).

5b Human voice: Ventricular fold phonation

Human voice might be regarded as a special case of wind instrument. The source oscillations are mainly defined by the inertial and viscoelastic properties of the vocal folds and the aerodynamic parameters of the airflow passing them, while the feedback from the air column upon the vocal fold oscillator is generally of minor significance. Yet, a particular type of voicing seems interesting from the point of view of wind instrument acoustics, viz. the one produced by some Tibetan monks and ethnic groups of Central Asia. This type of voicing is characterised by a very low fundamental frequency and a loud tone, rich in harmonics as compared to corresponding tones produced by Western bass singers (Smith et al., 1967; Barnett, 1977; Dmitriev et al., 1983; Campbell & Greated, 1987; Zemp, 1996). The underlying mechanism has not been clearly explained. This raises the question whether structures other than the vocal folds could play the role of an oscillator.

It seemed reasonable to assume that the ventricular (or false) vocal folds vibrate in such voice production. The geometrical configuration of these structures differs considerably from that of the vocal folds. As can be seen in Figure 1, Paper VI, the ventricular folds have a downward angulation. Thus, they can serve as a closing valve, preventing exhalation at high intrathoracic pressures, such as during the initiation of coughing. The vocal folds have the opposite angulation, so that they can serve the purpose of closing the airways during inhalation, such as in hiccup. According to Helmholtz (1863), the valve systems represented by the reeds in musical instruments may be classified into inwards striking "tongues", or valves (e.g. reed woodwinds), and outwards striking valves (brass instruments and voice). An interesting possibility studied in Paper VI was if they then function as an inward closing valve, i.e., similar to a woodwind reed.

6. Playing a reed woodwind

The skill to play an instrument is, as a rule, transmitted from master to apprentice, frequently with the help of "methods" and "études", see Figure 11. These serve as pedagogical complement to the objective study of accomplished works. Sometimes, such as in the cases of the Études for piano by Chopin or for guitar by Villa-Lobos, exercise pieces reach such a high level of musical quality that they become autonomous pieces of music.

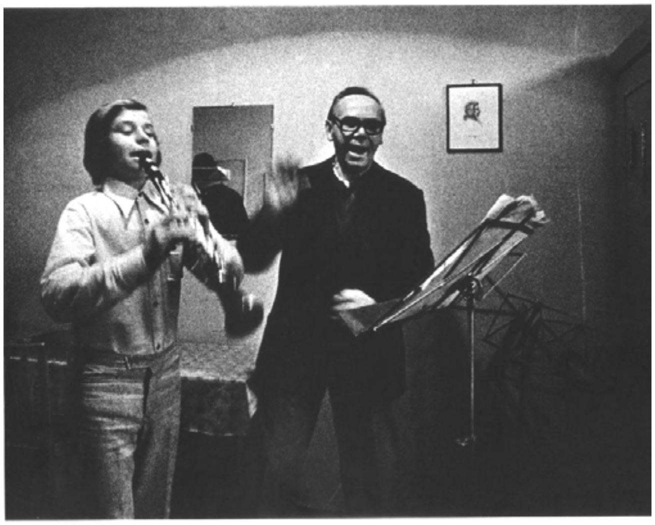


Figure 11. Clarinet Lesson. The master usually guides the pupil in every detail of performance, transmitting traditional techniques and esthetical values. The body posture and embouchure shown suggest that the picture was taken at the instant of a quick inhalation. Photo by Blei & Baumann (1987).

In general, the pedagogical material is expected to offer repetitive drills and playing challenges. It is presented to the student in a suitable order and sequence of complexity so as to promote the gradual development of the student's playing technique. Also, students tend to imitate the playing characteristics of their teachers. This is often considered desirable. Very seldom a professional-level classical player is self-taught, while this may occur often in other musical contexts.

In our Western culture, the education in classical music performance belongs to a rather well-established international tradition which, however, allows for some regional/national characteristics. During this process of observation, learning and training, players often develop a strong feeling of identification with musicians with whom they share playing characteristics of their "school". Also, they often have a tendency to reject "schools" representing other stylistic and technical practices.

However the differences in playing technique between different schools seem somewhat exaggerated. A given instrument requires a certain basic behaviour on the part of the player. In addition, the instruments seem to become more and more standardised and a small number of instrument makers dominate the professional market. Also, globalisation in the recording industry and an international job market contribute to reduce the effects of nationality and "schools". As a consequence, the use of professional classical players as subjects in performance experiments tends to be geographically and culturally independent.

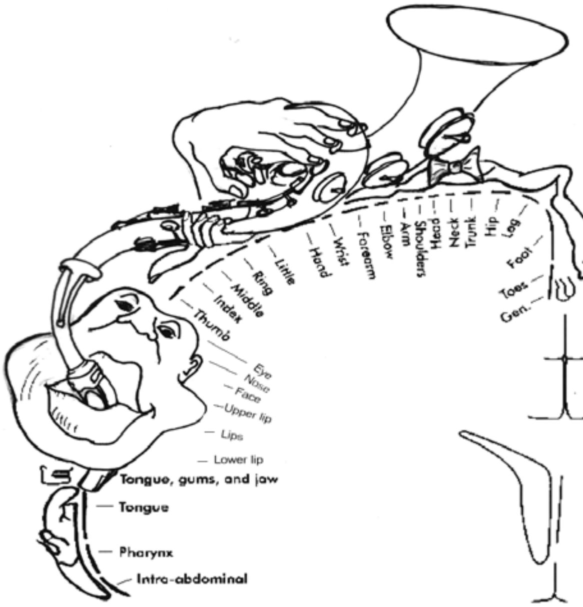
Apart from embouchure that has been already mentioned, posture and respiratory movements are regarded as crucial bodily aspects of performance in wind instrument along with the fingering technique. Interestingly, the latter would seem to the layman as the prime factor of playing.

Body posture is part of the performer' visual communication and can be at least partially assessed by the eyes of an experienced instructor, see Figure 11. Respiratory movements, by contrast, are much subtler and often not easy to observe by eye. In addition, posture and respiratory movements are intimately related. For instance, a maximal inhalation often requires changes of posture; a fixed expanded chest posture entails severe exhalatory constraints. A non-invasive respiratory measurement technique, respiratory inductive plethysmography, RIP, was used in Paper IV for objectively monitoring and recording of respiratory movements in performance. It measures variations in cross-sectional area for the estimation of internal thoracic volume changes. Therefore, postural changes that are independent of lung volume variations were expected to generate artefacts. This issue is examined in detail in Paper IV. We believe that this method may be useful for pedagogical and clinical purposes, as it allows monitoring of respiratory movements during musical performance.

A player must resort to many different techniques in realising musical ideas. Some of these techniques, which depart from the traditional ones, are called "extended techniques". In this thesis, some of these techniques have been mentioned and even investigated. One is circular breathing, where the player inhales while maintaining airflow from a reserve volume stored in the mouth cavity. This technique was even used as an experimental task in Paper IIIb. Other extended vocal techniques, such as vocal-ventricular mode phonation, periodic pulse phonation (Strohbass) and growl, are all considered in Paper VI.

Vibrato is a conventional and widespread effect in music. It has been an object of study from different areas, such as music acoustics (Meyer, 1991; Prame, 1994, 1997), music perception and psychology (Seashore, 1932, 1936, 1937, 1938; Brown, 1991), electronic music, and physiology (Gärtner, 1973; Titze, 1994; Hirano et al., 1995).

More effort seems to have been invested into the understanding on how vibrato is generated, than into how it can be practised and taught. Yet, the mechanism generating the vibrato in the wind instruments considered here is far from being exhaustively elucidated. Many musicians and even educators support the idea that vibrato develops "naturally", provided the playing technique is appropriate, and the instrument is "tuned" and properly set. The physical and physiological interpretation of these conditions is however unclear. Against this background it seemed important to examine physiological and aerodynamical aspects of vibrato production. This was ca



Pl a complex of body movements. It re hose related to hearing, touch in er ion. In order to illustrate the co vith wind instrument playing, the di the classical picture presented by P gure shows how the extroceptive se nperature and pain, are represented o f the areas of the parietal cortex

Figure 12. An attempt to a musical parody of the sensorial homunculus representing a player's somesthetic cerebral corte in terms of the areas employed during music performance. Adapted fron Penfield & Rasmussen (1950).

corresponding to the different parts of the body are mapped. The figure reveals that the lips, tongue and fingers occupy wide areas on the brain surface, particularly as compared with the correlative skin areas. A comparable diagram could be drawn with respect to motor functions, based on the motor homunculus proposed by the same authors.

Apart from the extroceptive sense, proprioception is highly important, being responsible for sensing the excitations in muscles, tendons and joints. This reflects body movement, position and, particularly in wind playing, blowing pressures and aspects of embouchure. In the case of embouchure, extroception and proprioception seem intricately related, since the contraction of the mouth muscles is converted into action on the oscillating reed, which feeds back an intense stimulation of the tactile receptors in the lips. In the case of perception of blowing pressure, however, it can be assumed that the main component is proprioceptive due to the fact that respiratory mechanics involve a great number of muscles, tendons and joints. This is suggested to dominate over the tactile sensitivity of intra-abdominal and trunk parts, as illustrated by the reduced cortical representation in the homunculus, Figure 12. In order to assess the proprioception of blowing pressure in wind players, independently of the other stimuli that usually concur during musical performance, an experiment was devised using a psychophysical production method, Paper V.

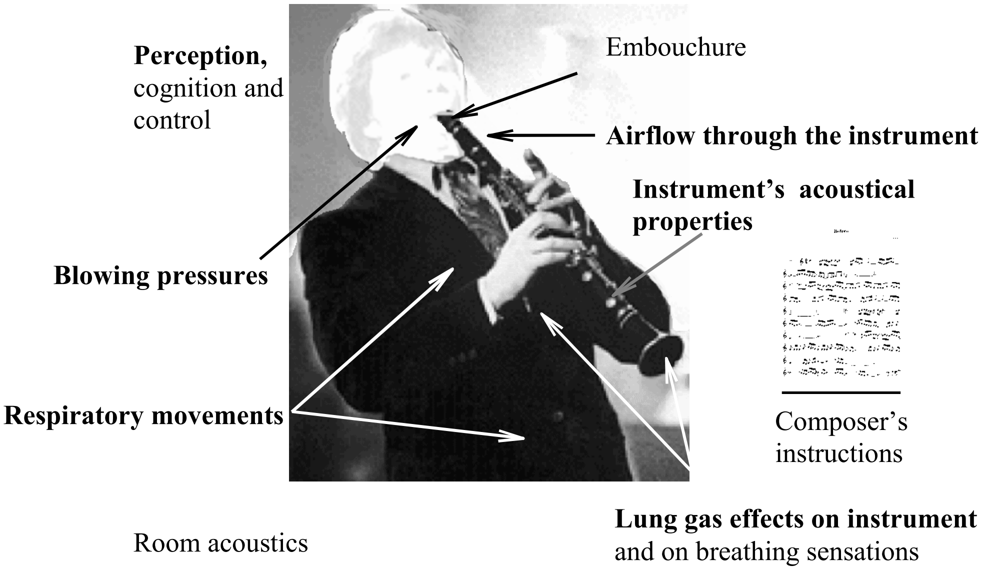

Perception,
cognition and
control
Embouchure
Airflow through the instrument
Instrument's acoustical properties
Blowing pressures
Respiratory movements
Composer's
instructions
Room acoustics
Lung gas effects on instrument
and on breathing sensations

Figure 13. A diagram showing the breathing-related aspects and factors involved in wind instrument playing, and those selected for investigation in this thesis (in bold letters)

Given the multitude of factors involved in wind instrument playing, it was necessary to select those, which were both relevant and feasible to study, see Figure 13.

Blowing pressures were investigated in Papers I and II, where the relationship with pitch, airflow and loudness were considered. From the results it could be assumed that the perception of blowing pressure is a highly relevant factor in wind instrument playing. This assumption was tested in Paper V. Also, there was no detailed information on how those pressures and flow were generated in terms of respiratory movements. This issue was examined in Paper IV. Considerable variations in pulmonary gas, particularly CO_2 and O_2, can be expected during playing. These variations seemed great enough to affect the instrument's acoustical properties with respect to pitch. The variations and their effects were studied experimentally in Papers IIIa and IIIb. Composer's instructions are normally encoded in a score, representing the typical input to a player. It contains instructions regarding rhythm, dynamical level, pitch, breath pauses and phrasing, all factors considerably affecting the player's breathing and blowing. In our experiments it seemed advisable to use normal-looking scores in describing tasks, since the form of instruction may be relevant to the player's behaviour. The acoustics of the room represents a factor generally considered of major importance to music performance and hence to the players' behaviour. For example, the scaling of dynamic levels (Paper II) and the duration of breathing pauses (Paper IV) can both be expected to vary with this factor. Embouchure is another factor of great significance in wind instrument playing, as explained above. For reasons of limitation, these two last mentioned factors were not studied in depth in this thesis.

It should be borne in mind that the ways of playing reed woodwinds are not exhaustively definable. The instruments are still in their evolution process, in terms of both bore/tonehole design and mechanics, stimulated by a continuous contribution of new research and applied technologies, while still keeping a long-term manufacturing tradition, see Figure 14. New design and materials for the reeds are under continuous development and so is contemporary music, with new requirements and potentialities. Also, the demands on the professional musician are not static. For instance the interaction of mechanical and electronic intruments and multi-instrumentalism, for which the artist must be able to perform on different instruments may be helped by a technology and technique that combines some of the control particularities of different instruments. This development may be furthered by a systematic research in music acoustics and music performance.

Figure 14. The final rehearsal. Making an instrument requires meticulous craftsmanship and performance tests. Subtle modifications in form and dimension affect the sounding and playing properties. Photo by Blei & Baumann (1987).

7. Basic ideas and methods

The basic idea behind our investigation on wind instruments was that respiratory acts in playing derives their characteristics from three different realms, (1) the acoustical properties of the instrument, (2) the physiological characteristics of the player, and (3) the musical demands of the score. As illustrated in Figure 1, these three realms are closely intertwined. To elucidate the relations between them, more detailed descriptions of the associated phenomena are needed. Such descriptions must be based on experimental work, requiring the use of an ensemble of methods of measurement as well as the selection of appropriate tasks.

Our research has been done with the assumption that the knowledge gathered from a predominantly physical approach should preferably be complemented by measurements collected under conditions that appear realistic to the players. This can be expected to result in additional and relevant aspects of the instruments influenced by the human factors in the relationship player/instrument.

The subjects in all wind instrument studies were adult healthy players, representing the western classical tradition. All subjects were either professional or semi-professional with more than 10 years of continuous experience. This was motivated by the belief that successful and experienced players use their instruments in a way that involves several processes of optimisation. Such optimisation can be expected as a result from long-term learning and experience and should lead to automated behaviour. This does not imply that there is a unique solution to any given performance problem, posed by the music, the instrument or the player’s physiological abilities and constraints. On the contrary, players can be expected to tailor their solutions to conditions represented by their instrument, and to their personal preference and physiology. No more than two players were used for each instrument. This was considered sufficient for the questions raised in the thesis, its main aim being to describe and explain aspects of wind instrument playing of players who are sufficiently skilled to earn their livelihood from playing. On the basis of our results, variations of playing technique should be more meaningful to examine in the future.

The experimenter strived for establishing a professional relationship with the subjects. All subjects were paid for their services, as artists should always be compensated when their professional competence is used. Moreover the payment may have contributed to eliciting a professional attitude to the solution of the various experimental tasks which were sometimes repetitive and demanded a high degree of concentration. The experimental sessions lasted for a full hour, approximately. The subjects were minimally informed about the purpose of the experiments.

It was considered desirable to ask the subjects to perform musically common tasks, such as scales, arpeggios, and well-known music examples. This was expected to induce their typical instrument playing behaviour.

Because the use of typical playing conditions was a main concern, methods that the player could regard as invasive or disturbing were avoided as much as possible. For the studies involving blowing pressure measurements, Papers I-II-IV-V, a thin pressure sensor (Gaeltec CTO-2 strain gauge catheter, 2mm diameter) was inserted in the player’s mouth corner and fixed to the face with adhesive tape. According to the subjects, this only marginally affected their embouchure. The respiratory inductive plethysmography (RIP) technique, applied in Paper V, is in essence a non-invasive method, since it measures external surface variations to infer internal thoracic volume changes. For the sake of accuracy, a fixed and rather symmetrical body posture is required. On some rare occasions the subject failed to meet this demand which caused interruption of the recording. In all such cases the professional player then promptly and successfully accomplished the repeating of the task with a stable posture. The use of the pneumotachometer (or electrospirometer) in Papers II-IV-V, did not cause any difficulties, since the subjects inhaled through it after exhalatory tasks, the mouthpiece being available from the hands of the experimenter whenever necessary.

In the investigation of vocal-ventricular phonation, Paper VI, several methods were used. For measuring the glottal flow, a Rothenberg mask (Rothenberg, 1973) was attached to the subject’s face, covering the mouth and the nose. This did not appreciably disturb sound production. In obtaining the images from the glottis by high speed filming, a rigid telescope was inserted in the subject’s mouth and held by the medical expert in the pharynx, allowing view of the ventricular folds. This method is clearly invasive, but it could successfully be applied after some attempts. For the preliminary videolaryngo-stroboscopy technique, a thin fiberoptic catheter was inserted through the nose and placed above the larynx. This did not disturb sound production. In recording subglottal pressure, a thin catheter was inserted through the nose, placed in the esophagus below the level of the larynx. Local anesthesia was required to prevent irritation and disturbance of voice production.

In the present thesis, we have strived for selecting questions which are both acoustically and musically relevant. In designing experiments a basic idea was to take advantage of the artists’ skills and long-term experience, thus hopefully attaining information collected under musically realistic conditions. Moreover, it was considered important that the scientist understand the artist’s frequently intricate questions.

8. Summaries and comments on individual papers

Paper I. "Blowing pressures in bassoon, clarinet, oboe and saxophone"

Blowing pressure is a major input parameter in wind instruments. In previous investigations, some data had been published on this topic (Bouhuys, 1964, 1968; Navrátil M & Rejsek K, 1968; Pawlowski & Zoltowski, 1985, 1987; Bak & Doemler, 1987; Cossette, 1993). However, there was a shortage of systematic measurements describing details of the relationship between pitch, blowing pressure and dynamic level. Also, some previous studies reported results collected from huge numbers of players, including professionals and students, presumably obscuring systematic dependencies between the three parameters mentioned. The aim of many of these studies was mainly to provide typical and maximal pressure values for clinical applications. The basic hypothesis tested was that a systematic relation exists between blowing pressures and the acoustic properties of the instrument and of the tones produced.

We recorded blowing pressures in the mouth cavity of two professional players of each of four reed woodwinds (Bb clarinet, alto saxophone, oboe, bassoon). The players performed three different tasks: (1) a series of isolated tones at four dynamic levels, (2) the same series with a crescendo-diminuendo tones and (3) ascending-descending musical arpeggio played legato at different dynamic levels (pp, mp, mf, ff). The results showed that, within instruments, the players' pressures exhibited similar dependencies of pitch and dynamic levels. Between instruments, clear differences were found with regard to the dependence on pitch. As can be seen in Figures 14-15, 20-21, 26-27 and 32-33, each instrument presented characteristic curves, differing only slightly between players.

Vibrato was not an object of study in this project, and the players were asked to avoid it, since it could be assumed to be associated with variations of the blowing pressure. Yet, some players occasionally produced a vibrato, as can be seen in Figure 6, p 44. In that particular case, the average blowing pressure was approximately 13 cmH_2O, while the amplitude of the vibrato oscillations varied between 1.5 and 3.0 cmH_2O peak-to-peak. This considerable modulation (about 10-25%) was still associated with a rather moderate vibrato effect. For a greater vibrato and at higher dynamical levels and pitches, even larger pressure modulations can be expected. This issue was investigated in Paper II.

The investigation focused on isolated, sustained tones, crescendo-diminuendo tones and arpeggi at fixed dynamical levels. We might assume that similar patterns would be found for other notes in the range studied and that blowing pressures for intermediate notes can be estimated by interpolation (see Paper I, Appendix, Table A). However, the fingering and the instrument's responsiveness do not necessarily vary continuously between adjacent tones, and this may demand differing pressure values. Tone variations occurring in the playing of real music may require much more complex pressure changes, see Figure 1, Paper V.

The Paper suggested that the proprioceptive functions in the respiratory system, which are responsible for the perception of stimuli by the abdominal, thoracic and lung receptors, are highly relevant to wind instrument playing. This was the main topic of Paper V.

The roles of the authors in this Paper were as follows: LF: Experimental design, recording, analysis of data, authoring the draft for the manuscript; JS: Consultation, assistance in experiment and in editing the manuscript.

Paper II. "Aerodynamic input parameters and sounding properties in naturally blown reed woodwinds"

This study can be considered a complementation of Paper I, which focused blowing pressure. The present paper corroborated and expanded the data from Paper I and added information regarding the airflow resistance of the reed. Also measurements of airflow were carried out, allowing estimation of typical demands on air supply in the different instruments - oboe, alto saxophone, bassoon, and clarinet.

Commercially available clarinet and saxophone reeds are usually specified with respect to "hardness", using an arbitrary scale ranging from 1 (soft) to 5 (hard). The "hardness" of a reed is defined by means of bending tests, i.e. in a way similar to that of measuring stiffness of materials in engineering (Vandoren Products Catalog, 1983). However, the “hardness” of a reed may be associated with a number of other properties as demonstrated by Fuks (1995) for clarinet reeds. Reed “hardness” is highly relevant to bassoon and oboe playing, and is generally adjusted by the players when they manufacture the reeds. The acoustical and aerodynamical correlates of the "hardness" have not been experimentally demonstrated. According to the general opinion among players greater “hardness” is associated with the need for higher blowing pressures and embouchure forces as well as with a “darker” tone quality.

Input aerodynamic parameters in reed woodwinds were measured when professionals played different pitches at three dynamic levels. Two reeds were used, one rated as a hard and another as a soft reed. The contrasting reeds in our experiment showed clearly different characteristics in terms of airflow, blowing pressure and resistance.

The tasks consisted of playing long sustained tones with and without vibrato. Audio and blowing pressure signals were recorded. Lung volume variations were indirectly measured by a spirometric procedure, which also showed the average air consumption, i.e. the mean airflow. The tones were played in a laboratory room and also in a calibrated reverberant chamber allowing estimation of radiated sound power. Average values for flow resistance, aerodynamical power, and mechanical efficiency were computed. Airflow and input power varied considerably between instruments and between the two reed types, but generally increased with sound level. Airflow systematically increased with blowing pressure and dynamical level in all instruments. The harder reeds required higher airflow, blowing pressure and tended to produce tones of higher SPL.

According to previous investigations the pressure-flow characteristic should follow a bell-shaped curve under conditions of constant embouchure tightness, see Figure 9, and only the falling part of the curve can be used in playing. Yet, our pressure measurements indicated that an increase of blowing pressure was associated with an increase of dynamic level. Thus, an increase of pressure seemed to produce an increase of airflow. This apparent discrepancy suggests that the player must reduce the embouchure tightness during a crescendo. If the player keeps a constant embouchure while increasing blowing pressure, the tone gets softer until eventually the reed simply closes.

Vibrato can be generated in different ways, as mentioned above. The investigation focused on an intense, or clearly audible vibrato. For vibrato tones produced on oboe, bassoon and saxophone, wide pressure oscillations were observed, on average 10 cmH_2O for the oboe and bassoon, and reaching values of 20 cmH_2O in some cases. These great undulations cannot be produced merely by the laryngeal mechanism, as claimed in previous studies, but must require participation of expiratory forces.

Paper IIIa. "Prediction of pitch effects from measured CO_2 content variations in wind instrument playing"

Paper IIIb. "Prediction and measurements of exhaled air effects in the pitch of wind instruments"

Paper IIIa, limited to the effect of CO_2 on tuning, was complemented by Paper IIIb, considering also the O_2 effects. The latter paper was

> compressed in size, to meet the demands for the proceedings of a conference. Therefore, a more elaborate account will be given here, also including some complementary examination of the results.

The studies reported in Papers IIIa and IIIb departed from a pilot study about respiratory conditions under different degrees of physical exercise and the effect of CO_2 in the lungs on maximal breathhold time. A capnometer, a device for measuring carbon dioxide percentage in the air (Bhavani-Shankar et al., 1995), was used for measuring CO_2 variations during performance on the oboe and the clarinet. This is a key gas in the respiratory control; the human body contains receptors that continuously monitor the amount of that gas, regulating the optimum level of gas changes and the rhythm of ventilation (Staub, 1991; Shea et al., 1996; Piiper & Scheid, 1982; Klocke, 1982; Flume et al., 1996; Fernando & Saunders, 1995; Banzet et al., 1996).

We observed wide variations in the CO_2 contents of exhaled air, usually starting from 2.5-3% and reaching up to 8.5% in extreme cases, after more than 50 seconds of playing without taking a new breath. This value exceeded those published as extremes in medical textbooks (e.g., Schmidt & Thews, 1983) and even in studies of the effects of breathhold during diving (Lin, 1987).

The effect of these great changes in gas composition on the intonation in these instruments was analysed. As mentioned, fundamental frequency depends on the sound speed in the air column in these instruments. Nedeerven (1969) calculated the effective sound speed for a flute, taking into account the effect of temperature and also the composition of the gas and assuming a CO_2 average of 2.5%.

In Paper IIIa, the variations in exhaled O_2 were assumed to vary linearly with time between 21% and 15%, the generally accepted range (Schmidt & Thews, 1983).

The study further assumed warmed up instruments, so that the temperature effect would not be interfering with the effect of gas composition. Also, it was postulated that the player started after a deep breath, inducing low values of CO_2 and high values of O_2. Simultaneous measurements of CO_2 and O_2 were realized in Paper IIIb.

Predicted and observed decreases of fundamental frequency amounted to 27 cents and 16 cents, respectively. The discrepancy might be accounted for by factors not considered in this paper. Thus, air humidity was assumed at a fixed 100% value, i.e., saturated vapour. As a complement, we present a calculation of the impact of humidity changes.

The idealised situation with a warmed up instrument is assumed, but with humidity increasing from ambient values to vapour-saturated air during the first moments of playing. As mentioned in Paper IIIa, sound speed c is calculated by equation 1.1,

$$c = (\frac{\gamma P_0}{\rho_0})^{\frac{1}{2}} \qquad \text{Equation 1}$$

an alternative equation, resulting from Boyle's law, is

$$c = (RT\gamma)^{\frac{1}{2}} \qquad \text{Equation 2}$$

where,

P_0 is the ambient pressure
ρ_0 is the gas density

γ , the specific-heat ratio, i.e. specific heat at constant temperature divided by specific heat at constant volume

R , a gas constant

T is the temperature in K

also,

$$R = \frac{R_0}{M} \qquad \text{Equation 3}$$

where,

R_0 is the universal gas constant , 8312 J/(kg.K)

M is the average molecular wheight of the dry composite gas.

This formula yields the same numerical results as those obtained by formulas 1.1 and 1.2 in Paper IIIb. In accounting for the effect of humidity, a thermodynamic formula valid for the narrow range of variations in temperature and in gas compositions (e.g. Pierce, 1981) is:

$$c_{wet} = [1 + 0.16H]c_{dry} \qquad \text{Equation 4}$$

where,

c_{wet} sound speed in the humidified gas,

c_{dry} sound speed in dry gas,

H fraction of H_2O molecules in the air

From thermodynamical tables (ASME, 1967) it can be calculated that for saturated vapour at 40°C, the value for H is 0.07, approximately (Pierce, 1981). For a variation from 40% ambient humidity to 100% inside an instrument, i.e. reaching 60%, the isolated contribution of humidity should be approximately:

$$c_{100\%} = [1 + 0.16 * 0.042]c_{40\%} \qquad \text{Equation 5}$$

According to Equation 5 the increase in sound speed due to humidity should amount to 0.67%, or 12 cents in fundamental frequency for the sounds produced. This amount should oppose the expected maximum shift of -27 cents, due solely to the CO_2 and O_2 changes. The net shift of -15 cents seems realistic, as compared to approximately -16 cents observed in Paper IIIb and shown in Figure 3.

As pointed out in Paper IIIa, the impact of the effect of the gas mixture should also indirectly depend on the airflow. Paper II offered some experimental data regarding airflow through four reed instruments. The volume contained in an adult player's upper airways, or the physiological dead space, amounts to approximately 150 ml. In cases of low airflow, it could take as much as 3 or 4 seconds for the intrapulmonary air to reach the reed. This would be the most critical phase for the gas effects on the intonation, as shown by Figures 2 and 3 in Paper IIIb. During that period, the quasi-ambient air would be fed to the instrument bore, and thereafter intrapulmonary air. In cases of high flow, the effect of the transient gas density will occur at the same time as other transitional processes, such as the onset of the tone, the adjustment of pitch and dynamic level, etc. Once the pulmonary air has filled the entire instrument a slowly changing effect on the fundamental frequency can be expected.

Papers IIIa and IIIb demonstrated that the discussed effect of gas changes may be a relevant factor in performance.

The outcomes of this study can be demonstrated by a simple experiment that may be useful in a music classroom. It requires a reed woodwind instrument, a manometer connected to the player's mouth and an electronic tuner. After warming up, the subject will play a long steady tone at pp, keeping a fixed embouchure and blowing pressure as displayed by the manometer. Another observer will monitor the fundamental frequency as indicated by the tuner. The subject may blow a long tone interrupted by occasional brief pauses, without breathing. This is not expected to change the tuning. Then, the subject quickly exhales the remaining air in the lungs and resumes playing after a quick and deep breath. This time, an effect on tuning can be expected. This obviously is a simplified and less well-controlled version of the experiment described in Paper IIIb.

Paper IV. "Respiratory inductive plethysmography measurements on professional reed woodwind instrument players"

In Paper II, airflow in long sustained tones, played at different pitches and dynamic levels was measured. This, obviously, is a rather particular playing condition. To collect data from real performance a different method should be applied. As mentioned, the multiple factors in sound production in wind instruments make it a hard task to measure airflow directly, without severely affecting the system.

Respiratory Inductive Plethysmography (RIP) is a technique devised for clinical respiratory monitoring, introduced in the end of the 70's. It is still in frequent use as it is reliable, robust, non-invasive, intrinsically safe and represents a relatively low cost method (Chadha et al. 1982; Strömberg, 1996). The technique is based on the principle of self-inductance of a coil, which is connected to a high-frequency oscillator. Elastic bands are wrapped around the chest and abdomen of the subject; the bands are provided with an electric coil powered by the oscillating unit, see Figure 1 in Paper IV. The changes in the cross-sectional areas surrounded by the coils cause changes in the electromagnetic properties of the system. Thus, the individual variations of chest and abdominal volumes produce corresponding variations in the output signal of the RIP. The method is closely related to the two-degrees-of-freedom model for measurement of chest wall volume displacements (Konno and Mead, 1967; Loring and Bruce, 1986). According to this model, the variations in lung volumes are solely reflected in the variations of the two independent compartments, the rib cage and the abdomen, although a good accuracy can be attained only provided that there is no change in body position. The technique has been successfully applied to the analysis of respiratory movements in singers (Thomasson and Sundberg, 1997). In addition, studies have been carried out on the relation between respiration and phonation (Iwarsson et al., 1996). Regarding wind instrument playing, one single investigation (Cugell, 1986) has been published, particularly considering brass instruments and presenting mainly qualitative data.

Since high pressures had been observed in playing (Papers I-II) and some wide respiratory movements could be expected, as compared to previous applications of RIP, suitability and accuracy were main concerns. One attempt to assess the method was to apply the RIP band around a calibrated cardboard box, which permitted oblique angular distortions, i.e. changes of rhomboid cross-sectional area while keeping constant perimeter, see Figure 15. As shown, the output of the system was linear for a wider range than that equivalent to abdominal dimensions.

Additional calibration procedures were used to check the RIP accuracy in the pressure and lung volume ranges used in wind instrument playing. These experiments are described in Paper IV.

The method was then applied to eight professional players of the four reed instruments, who performed different musical and respiratory tasks. It yielded acceptable accuracy for the measurement of lung volumes, relative abdominal and rib-cage movements and also for the temporal and kinematic details of brief breathing pauses. Particularly challenging demands on respiratory technique were presented in terms of JS Bach's piece (solo obligatto from Cantata 147). Its long, "motoric" phrases played at a fast tempo, did not offer suitable breathing spots to the players. This reflected on the respiratory patterns and also as short duration of the breath pauses. The RIP method turned out to be appropriate even under these extreme conditions. It thus seems applicable to wind instrument performance research in general and should be useful also in pedagogy. In addition, a computer program was written and implemented for the use in portable computers with an acquisition card, allowing real-time calibration and data display.

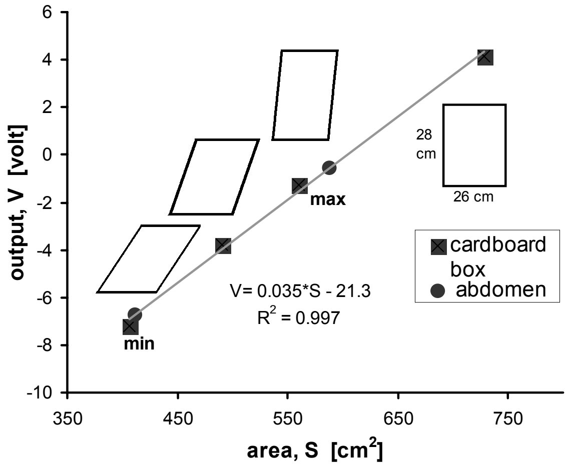


Figure 15. Test of RIP linearity: squares show the linear output obtained when the angles of a rhomboid box, fixed perimeter of 108 cm, with a RIP band attached, were changed. The line represents the best linear fit (R^2=.997). Filled circles show minimum and maximum output voltages for abdominal cross-sectional area in a subject.

Breath groups were initiated at 55% - 87% and terminated between 14% - 52% of the players' vital capacity, depending on instrument, piece, and phrase length. The players generally showed simultaneous and in many cases equally important contributions from rib cage and abdominal wall during playing. These findings often contrasted sharply to the players' own ideas on how they used their respiratory apparatus. The findings departed from what had previously been found for singers, who tend to resort mainly to chest wall movements for generating lung volume changes. In extreme cases, inhalations were achieved in approximately 300 ms and reasonably synchronised with the RIP signals.

The roles of the authors in this paper were as follows:

LF: Pilot studies on the RIP method, using different calibration procedures and carrying out recordings and data processing from the performance of several musical tasks with the different instruments; design of the experiment; running the experiments; processing of experimental data; writing of the paper; discussion of paper with co-author JS

JS: discussion on experimental protocol; running the experiments; writing of the paper; discussion of paper with co-author LF

Paper V. "Assessment of blowing pressure perception in reed wind instrument players"

Paper V was exploratory in nature since it represented, to our knowledge, the first study ever on this modality of perception in musicians. Paper I showed that professional players change blowing pressure systematically according to instrument, pitch and dynamic level. This indicates that players must possess the ability to accurately sense the pressures they generate. It is obviously a prime control variable along with other parameters, such as the auditory feedback and the sensations in the embouchure.

The investigation applied a psychophysical production method for direct assessment of the blowing pressure perception in professional players. The main object of the study was the investigation of how the players judged mouth pressure, independently of normal playing conditions, i.e. without embouchure effort, reed vibration, airflow or auditory feedback.

The players were asked to produce static mouth pressures corresponding to a set of numbers that were given to them, one by one and in random order. The pressures thus produced were recorded and measured and then compared with these numbers.

The method provided consistent data representing interesting information about this rarely studied modality. Regression analysis revealed that a linear model yielded the highest correlation between measured and perceived pressures. Linearity is not generally found for other perceptual modalities, such as loudness and pitch. The method, however, did not allow for the estimation of the difference threshold, a relevant parameter for quantifying sensation.

The considerable inter-individual differences in sensitivity indicate that average values are not adequate to predict the behaviour of subjects in general terms. We used a limited group of subjects, all of them players of reed woodwinds. It would be worthwhile to include more subjects and players of other wind instruments in future investigation. To complement the result of this paper, other methods could be applied in the future, such as cross-modality comparisons.

Paper VI. "A self-sustained vocal-ventricular phonation mode: acoustical, aerodynamic and glottographic evidences"

Human voice is a result of a complex interaction between anatomical, physiological, neurological and cultural factors. The immense variety of vocal sounds encountered across the cultures of the world demonstrates a multitude of possibilities for using the voice organ (e.g. Zemp, 1996).

The role played by the ventricular folds (Figure 1 in Paper VI) in voice production still constitutes an open issue. Some authors suggested that the ventricular folds were responsible for producing the lowest tones, while the vocal folds would be generating the higher tones. It even has been claimed that the ventricular folds produce falsetto tones, speculations that were refuted already by Garcia (1855). Yet, it has remained unclear how the ventricular folds can be used in sound production, e.g., under pathological conditions such as in ventricular dysphonia (Freud, 1962).

A particular vocal effect, found in certain Asian cultures (Tibet, Mongolia), is associated with a very low fundamental frequency and a dense spectrum. This type of voice production had been documented in previous studies in voice science, ethnomusicology and music acoustics (Smith et al., 1967; Campbell & Greated, 1987; Barnett, 1977; Ellington, 1970), however without exhaustive explanation of the underlying sound production mechanism.

The initial hypothesis was that the mechanism employed includes the ventricular folds. For some years the first author attempted to learn this particular phonatory technique assisted by analysis resources provided at KTH-TMH. The attempts were successful according to expert testimony. This appeared to justify the use of the first author as a subject in the experiment, particularly since Tibetan monks in Sweden seemed hard to access.

Co-operation with the Karolinska Institute, offered the possiblility to obtain images derived from two different techniques, videolaryngo-stroboscopy and high-speed glottography.

The results of Paper VI revealed that, under special conditions, the ventricular folds vibrate periodically in cooperation with the vocal folds. Results did not corroborate the initial hypothesis that the ventricular folds vibrate in a reed-like fashion, i.e., as an inward striking valve. Rather, they vibrated more like the vocal folds and seem to importantly contribute to the primary sound generation in the mode of phonation used in Tibetan chant. The results suggested that, in spite of striking similarities with regard to spectral appearance, this type of voice production is different from the one used in the production of periodical vocal fry, such as in the so-called Strohbass register.

The participation of the authors in the paper was as follows:

LF: idea, planning and design of experiments, serving as the sole subject, data analysis, design of the VVM model, writing of first draft

JS: revision and discussion of the manuscript

BH: providing the possibility to high-speed imaging, expert advice and revision of the manuscript

9. Music continues; a list of possible future investigations

The interdisciplinary approach taken in this thesis has touched upon a number of issues that have been left aside for reasons of limitation, but that seem worthwhile to study in more depth in the future. Such points, some of which already addressed in pilot studies, will be enumerated below in the form of the author’s "wish-list".

- Blowing pressures during performance, including a larger number of subjects of different levels of skill.

- Development of a computer system that assists in the training and evaluation of the control of blowing pressure. For example, it could present visual pressure targets that should be reached by means of a mouth pressure controller. Such a system can be expected to improve the player’s pressure control and thus facilitate learning.

- Analysis of various acoustic, physiological and perceptual aspects of vibrato in reed woodwinds.
- Use of up-to-date techniques for measuring airflow directly in the instrument bore.
- Physiological and acoustical measurements of embouchure, providing elements for physical modelling of this rarely studied factor of sound production in wind instruments.
- Analysis of occurrence of tuning deviations during performance and their relation to the effect of variations in the exhaled gas.
- Investigation by means of RIP of the consistency of the respiratory movements in professional and novice/apprentice players.
- Psychophysical studies on perception of blowing pressure employing cross-modality comparisons, including determination of difference thresholds and comparing players of different skill level. Also the relevance of age can be studied.
- Determining breathhold and optimal playing times, taking into account different playing demands and the player's physiological characteristics. The results should be compared with corresponding measurements on divers (e.g. Lundgren & Ferrigno, 1987).
- Expanding the database on breath pauses and phrase lengths, and implementing the results in an algorithms for automatic simulation of music performance.
- Refining and assessing the VVM model by computer simulations.
- Extending the investigation of the VVM phonation to periodic pulse register, and developing a physical model.

10. Conclusions

Our investigations confirmed that respiratory acts in wind instrument playing derives their characteristics from three different realms, (1) the acoustical properties of the instrument, (2) the physiological characteristics of the player, and (3) the musical demands of the score. This supports the assumption that an interdisciplinary approach to the study of sound production in wind instruments is likely to yield more information and to open new perspectives, promoting understanding of several, otherwise confusing and intangible issues.
Here follows conclusions ordered according to the papers presented.

Paper I

- Blowing pressures represent a factor of major relevance to playing.
- Blowing pressure is varied systematically with dynamic level and fundamental frequency in the instruments studied; these dependencies seemed consistent within as well as between players
- In doublereed instruments pressure was increased with fundamental frequency while in the clarinet the pressure tended to decrease with fundamental frequency within each register and in the saxophone, it was varied according to a pattern similar to that of doublereeds in the lowest octave, and similar to that of the clarinet in the higher range.

Paper II

- The hardness of the reed affects various input parameters, harder reeds requires higher airflow, blowing pressure and tend to produce tones of higher SPL.
- Airflow systematically increased with blowing pressure and dynamical level in all instruments.
- Players tend to simultaneously increase blowing pressure and decrease the tightness of the embouchure, when they increase dynamical level. For constant embouchure an increased blowing pressure produces a softer tone.
- Intense vibrato in reed woodwinds was associated with comparatively wide pressure undulations. These undulations cannot be produced merely by the laryngeal mechanism described in previous studies but rather with participation of expiratory forces.

Paper III

- During playing wind instruments the content of CO_2 in the expired air varies between the ambient level and up to 8.5% in extremely long phrases, while for the O_2 it may vary from the ambient 21% down to 12%, or even less.
- The increase in CO_2 tends to lower the pitch and the fall in O_2 tends to raise it. The net effect is a pitch decrease.
- Air humidity, on the other hand, changing at each new breath, tends to increase pitch.
- The overall effect of these factors may account for a fall in fundamental frequency by more than 15 cents.
- The player may compensate for these relevant pitch effects by means of the embouchure and blowing pressure.

Paper IV

- The non-invasive RIP method revealed to be robust and reasonably accurate also when applied to wind instrument playing.
- Spirometry indicated that the relationship between the RIP output and lung volume was linear within the typical ranges used in reed woodwind instrument playing.
- Artefacts were caused by posture changes and by the compression of the respiratory system required at high expiratory pressures. Compression artefacts can be partly compensated for by postprocessing of the data, taking the blowing pressure into account.
- Initiation lung volume (ILV) typically ranged between 55% and 87% of vital capacity (VC) in the pieces tested.
- For instruments that require blowing pressures in the range of the relaxation pressures, i.e. up to 40 cmH_2O approximately, termination lung volume (TLV) reached values close to 0% VC in extreme cases.
- For instruments requiring higher blowing pressures such as the oboe, TLV values below rest end-expiratory level (REL) were rarely observed.
- During a highly demanding piece inhalation breath pauses were typically about 300 ms long and synchronised with increases of the RC and AW signals

- The RIP method, at least when complemented by spirometry and constant-flow procedure, should be useful for future research as well as for pedagogical purposes.

Paper V

- The factors involved in the perception of blowing pressure are complex and not easily isolated from each other, as these pressures are sensed by different organs and mechanisms.
- Still, reproducible and consistent data were obtained from highly trained players.
- The relationship between stimulus and perception was quasi-linear in almost all cases; a power function with the exponent generally close to 1.0 also represented an acceptable model. The power function exponents were mostly positively correlated to lung volume.
- Sensation of blowing pressure alone seems to provide an important clue for the musician's control of the instrument.
- Considerable inter-subject differences were found in estimated sensitivity; therefore, mean values are not adequate for predicting the behaviour of individual subjects.
- Psychophysical methods seem useful for assessment of playing abilities in players, and possibly for evaluating specific training programs designed to improve respiratory control in performance.

Paper VI

- The particular phonatory mode investigated in this exploratory study was associated with simultaneous oscillations of the vocal folds and the ventricular folds.
- The effect is similar to that produced in the Tibetan chant tradition, according to an expert listener.
- The frequency ratio between vocal and ventricular folds was 2:1 or, in some cases, 3:1.
- The closure of the ventricular folds occurs during the open phase of the vocal folds, thus damping every second or third glottal pulse.
- The driving of the ventricular folds seems to be a negative pressure generated by the airstream contained in the glottal pulse.
- The subglottal pressures required were consistently higher than those used in modal and pulse register, at least in the subject used in this experiment.
- The fundamental frequency range approached one octave starting at 49 Hz (G_1), approximately. The SPL measured at 0.3 m could be varied within 64 and 88 dBA for the 58Hz (Bb_1) tone.
- This technique can also be employed in wind instruments playing, producing a family of new sounds.

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Blowing pressures in reed woodwind instruments

*Leonardo Fuks*ℵ *and Johan Sundberg*

Abstract

The blowing pressures during wind instruments playing have not been systematically measured in previous research, leaving the dependencies of pitch and dynamic level as open questions. In the present investigation, we recorded blowing pressures in the mouth cavity of two professional players of each of four reed woodwinds (Bb clarinet, alto saxophone, oboe, bassoon). The players performed three different tasks: (1) a series of isolated tones at four dynamic levels, (2) the same series with a crescendo-diminuendo tones and (3) ascending-descending musical arpeggio played legato at different dynamic levels (pp, mp, mf, ff). The results show that, within instruments, the players' pressures exhibit similar dependencies of pitch and dynamic levels. Between instruments, clear differences were found with regard to the dependence on pitch.

Introduction

Blowing pressures in wind instruments, which range between 10 and 120 cm H_2O in reed woodwinds, have been a matter of interest in different fields such as respiratory physiology and pathology, occupational health, music acoustics, sound synthesis based on physical models and musical playing practice.

In medical sciences, the information on blowing pressures may be helpful to understand the etiology of some health problems in players and to evaluate the subject's capacity to perform various musical works.

In music acoustics, pressure data are required for comprehension of how the system consisting of player/instrument converts aerodynamic energy into sound. The complex relationship between input parameters (mouth pressure, air flow, and the embouchure, i.e. the constellation of forces and positions in the lip and mouth regions) and the resulting sound properties (pitch variations, loudness and sound quality) represent a challenging and promising issue in the physics of instruments.

For sound synthesis purposes, the input pressure at the instrument is a determinant parameter for sound production and thus required for a successful numerical modelling of the instrument.

In musical practice and education, objective facts regarding playing are valuable for the music teacher/performer and sometimes also for the composer, as such information may have important consequences in playing techniques.

Some earlier investigations have included data on blowing pressures in wind instruments. Bouhuys (1968) studied the oboe and clarinet and other instruments and presented pressure ranges for low and high tones. Navrátil & Rejsek (1968) observed that blowing pressures varied with dynamic level in clarinet, oboe and bassoon. Worman (1971) describes the behaviour of a clarinet in terms of the relation between flow velocity and blowing pressure but does not present any information on the dependence of pressure on dynamic level. Pawlovski & Zoltowski (1985) give some general pressure ranges for bassoon and clarinet, obtained from a numerous set of subjects, including students and professionals. Pawlovski & Zoltowski (1987) provided more specific results for two notes and two dynamic levels in clarinet, oboe and bassoon. Their main aim was to formulate a distinction between normal and pathologically reduced maximum playing duration for a tone. Fuks (1993) measured blowing pressures in clarinet at three dynamic levels, pitches G_3, F_4 and E_5, played by only one subject using four different reeds.

Summarizing, the data available on blowing pressures in wind instruments are scarce, particularly with respect to dependence on pitch and dynamic levels and confined to sustained tones, lacking a musical context. The purpose of the present investigation was to measure blowing pressures in wind instrument players at four different dynamic levels and at pitches covering the normal range of the instruments. For the sake of limitation, the investigation was

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ℵ *Universidade Federal do Rio de Janeiro, School of Music, Brasil* confined to four reed instruments, clarinet, alto saxophone, oboe and bassoon.

Material and method

Mouth pressure was captured by means of a thin pressure transducer (Gaeltec 7Sb) inserted in the player's mouth corner, so as to minimally affect the embouchure. The transducer was connected to an amplifier and one track of a multichannel TEAC (RD-200T) PCM DATA recorder. A sound level meter (Ono Sokki LA-210) and a microphone (Sony ECM-959DT), both at 1 m distance, picked up the audio signal and its SPL. The signals from both these devices were recorded on separate tracks of the same TEAC recorder. Experiments were run in a moderately reverberant room, volume close to 70 m^3 (615 x 460 x 250 cm).

The experimental protocol consisted of the following tasks:

1. Sustained tones (Table 1) in a series of ascending fifths, played four times at each of four different dynamic levels *forte*, *f*, *pianissimo*, *pp*, *mezzopiano*, *mp*, and *mezzoforte*, *mf*, duration of about 2 seconds each. This task was performed 3 times. These data will be referred to as f_s , mf_s , mp_s and pp_s .
2. The same sequence of pitches as in the previous item, in ascending and descending order, played *crescendo-diminuendo* from *pp* to *mf* to *pp*. Each tone had a duration of 3 seconds, approximately. This series was played three times. As expected, a pressure variation was observed during the tones, as illustrated in Figure 3. Therefore three pressures were measured for each tone, at the onset, at peak and at the termination. These pressures will be referred to as b_o , b_p and b_t.
3. Ascending and descending *arpeggi* (see table 1), tones of 1s duration, approximately, covering the typical pitch range of the instrument. These *arpeggi* were played *legato* at four dynamic levels (*fortissimo*, *ff*, *pianissimo*, *pp*, *mezzopiano*, *mp*, and *mezzoforte*, *mf*). Each level was played four times in succession. Henceforth, the data from this task will be referred to as ff_a , pp_a , mp_a and mf_a.

One of the pitches played in these tasks was common (marked with bold characters in Table 1). As can be seen in the table, this tone was located in the middle range of the instrument.

For all tasks, subjects were instructed to play as uniformly as possible with respect to tempo, sound quality and loudness. In task **3,** the players were instructed that *ff* and *pp* referred to the maximum and minimum possible loudnesses that could be produced, keeping acceptable tone quality. The intermediate dynamic levels (*mf* and *mp*), were left to the musician to decide. They were also asked to avoid vibrato, as it might be associated with a modulation of the blowing pressure.

Players were aware only of the fact that the experiment was related to blowing pressures and that it would take from 40 to 50 minutes. No other information was given until the entire recording protocol was completed.

Calibration

The Gaeltec output voltage was set to zero for ambient air pressure and for every experimental session the range knob was adjusted so as to accommodate the maximum pressures used by the player. After each experimental session, the transducer was immersed at various depths in a water column the lengths of which were measured and the associated output voltages were recorded. The precalibrated sound pressure level meter was exposed to two different SPL values (B&K Calibrator 4230) as references and the output voltages were recorded on the tape. All these calibration signals were also announced on the audio track of the tape. The relation between the Gaeltec output voltage to pressure was found to be linear, the errors being smaller than 1 cm of H_2O within the pressure ranges used; a typical example can be seen in Figure 1. Hence, the conversion from voltage to pressure was determined by means of a linear regression trendline applied to the calibration data.

Table 1. Tones used for the various tasks for the different instruments. Bold characters represent pitches common to all three procedures.

A4= 442 Hz

Instrument	**Series of Fifths** - tasks **1** & **2**	***Arpeggio*** - task **3**
Bb Clarinet *	F$_3$ C$_4$ **G$_4$** D$_5$ A$_5$ E$_6$	Eb$_3$ G$_3$ Bb$_3$ Eb$_4$ **G$_4$** Bb$_4$ Eb$_5$ G$_5$ Bb$_5$ Eb$_6$
AltoSax (Eb) *	F$_3$ C$_4$ **G$_4$** D$_5$ A$_5$	Eb$_3$ G$_3$ Bb$_3$ Eb$_4$ **G$_4$** Bb$_4$ Eb$_5$ G$_5$
Oboe	C$_4$ G$_4$ **D$_5$** A$_5$ E$_6$	Bb$_3$ D$_4$ F$_4$ Bb$_4$ **D$_5$** F$_5$ Bb$_5$ D6$_6$
Bassoon	C$_2$ G$_2$ **D$_3$** A$_3$ E$_4$ B$_4$	Bb$_1$ D$_2$ F$_2$ Bb$_2$ **D$_3$** F$_3$ Bb$_3$ D6$_4$ F$_4$ Bb$_4$

* refers to actual pitches rather than transposed notations

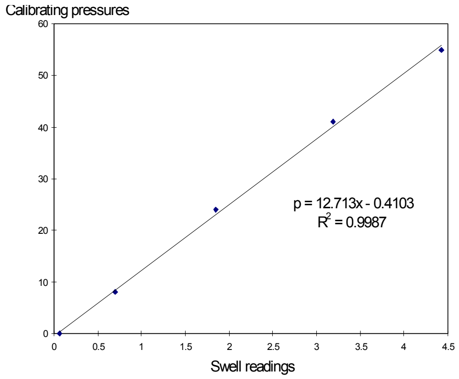

Figure 1. A typical pressure calibration curve. The transducer was dipped into water at depths of 55, 41, 24, 8 and 0 centimeters. The ordinate corresponds to values read at the Swell software files. The trendline was drawn by Excel which also calculated the line

Subjects and instruments

The subjects, two oboists, two bassoonists, two clarinettists and two saxophonists, were all professionals, and represented the western classical music tradition. All subjects had at least 15 years of experience of playing in symphony orchestras. Only one of them was female (clarinettist Cl1). The age range was 32 to 54 years. The musicians played on their own instruments and mouthpieces/reeds, that they used as their everyday working tools. Appendix B specifies the instruments used. As payment for their participation they received an amount approximately corresponding to a one-hour private lesson.

Analysis

The recorded signals were transferred from the Teac recorder into computer files, using the Swell DSP software package installed in a PC computer and an Ariel DSP-16 board.

Mouth pressure voltage was determined for each tone and exported to an Excel spread sheet. For each tone played at constant loudness, mouth pressures were averaged across the quasi-stationary part of the tone. Even for such tones the pressure curves rarely presented a perfect plateau-like shape. In such cases, representative values were determined by eye, with the aid of visual display and zooming, and also of audio playback from the data files. Figures 1, 2 and 3 show typical examples from sustained, *crescendo* and *arpeggio* tones. The mouth pressure voltages thus determined were then converted into pressure units.

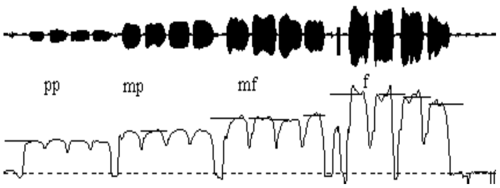

*Figure 2. Sound wave and pressure curves from player Cl2 obtained from Task **1** (sustained tones). The horizontal lines show the mouth pressure values selected for analysis.*

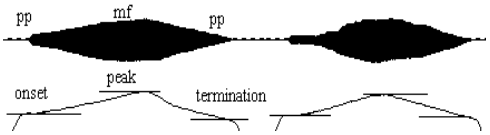

*Figure 3. Sound wave and pressure curves from player Ob1 obtained from two takes of a tone played in Task **2** (crescendo-diminuendo). The three horizontal lines show mouth pressures at onset, peak and termination.*

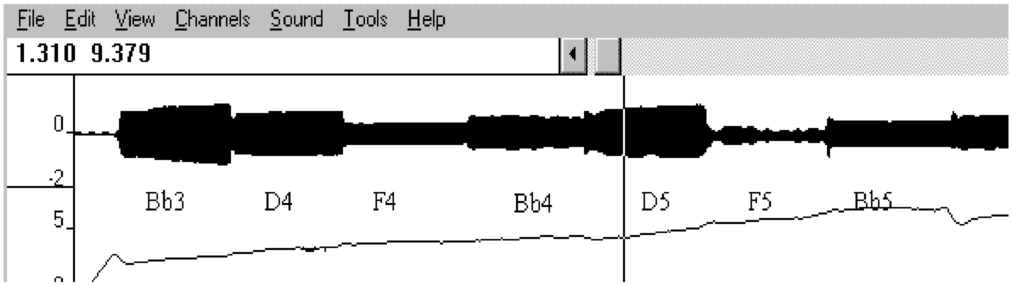

Figure 4. Sound wave and pressure signals as displayed by the Swell software. The pitch names are given below the corresponding tone segment.

For each pitch, mean values were computed across all takes and the standard deviations determined. In cases of four replications, these mean values ± one standard deviation represent a confidence interval of 95%, provided that a normal distribution of the data is assumed.

Results

In this section some examples of micro-structural features of pressure curves will be shown first. Then, the results will be presented instrument by instrument. For each instrument mean pressures measured during the *sustained tones* and for the *crescendo-diminuendo* tasks will be presented in terms of histograms. These data show the pressures used under quasi-neutral conditions. It is interesting to compare them with those observed in a musical context such as the *arpeggio* task. These values are displayed in sets of graphs where the abscissa represents the tone's position in the musical score. Averages and standard deviations are listed in tables in the Appendix A. Instruments are specified in Table B, Appendix.

Some micro-structural features of pressure curves

A set of characteristic pressure patterns were observed in the data. Although a detailed examination of them is beyond the scope of this study, they seem to deserve some comments, as they would illustrate the musicians' *modus facendi*.

Rising/falling pitch contour

In the *arpeggio* task some players increased pressure during each tone in the ascending part but not so in the descending part, as can be seen in Figure 5.

Vibrato

Although the players were instructed to avoid vibrato, some cases of inadvertent vibrato occurred. Figure 6 illustrates an example from the *arpeggio* task in *pp* played on the bassoon. A clear pressure modulation can be observed with an amplitude ranging from 1.5 to 3 cm H_2O. The frequency and phase of the modulation agree with the amplitude modulation.

Pre-tone pressure build up

Before the tone onset a pressure build-up phase was frequently noted that was followed by a pressure drop after the onset, which ended on the pressure used for the quasi-stationary remainder of the tone. Figures 7 and 8 show examples from sustained tones played on clarinet and oboe. Typically the duration of these pressure patterns ranged from 0.35 to 0.60 seconds, and in the case of the oboe, the amplitude of the peak, i.e. the difference between the peak and the subsequent quasi-steady pressure, ranged from 3.0 and 7.0 cm H_2O, at G_4 in *mf*. This phenomenon could reflect strategies needed for starting well-controlled reed vibrations.

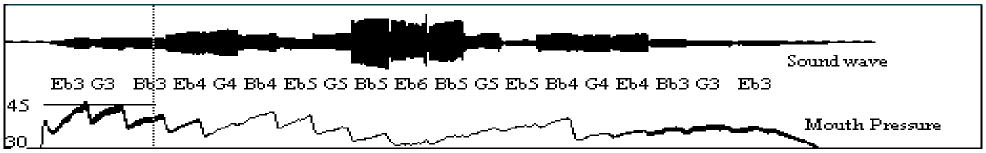

Figure 5. Pressure variations in Player Cl2 mf arpeggio*, take 2, illustrating the rising/falling pitch contour effect.*

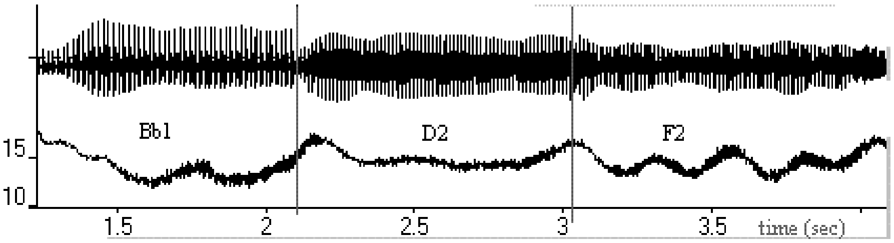

Figure 6. Examples of sound wave and mouth pressure modulation (upper and lower curves) during vibrato in the bassoon observed for notes Bb_1 *,* D_2 *and* F_2 *in the arpeggio task played in* pp*. Pressures in cm of* H_20*.*

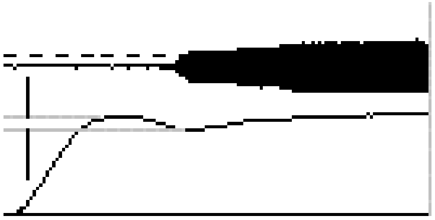

Figure 7. Pre-tone pressure build-up, Ob2, G_4, mf

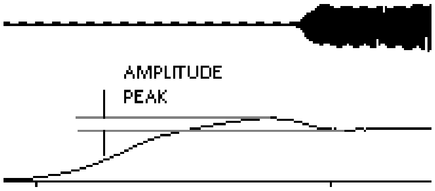

Figure 8. Pre-tone pressure build-up, Cl2, C_4, mf

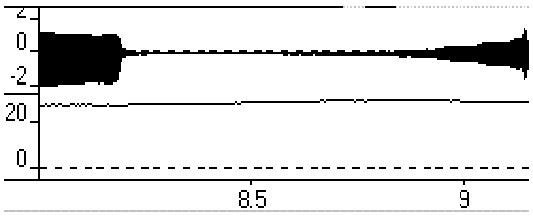

Figure 9. Pressure anticipating clarinet tone, Eb_6, mp*, player Cl2. Sound wave and mouth pressures are displayed in upper and lower curves. Pressures in cm of H_20.*

Strategies for producing difficult tones

Tones at pitch extremes are generally more difficult to play than other tones. In some cases, the players established a pressure supposedly suitable for the intended tone which, however, started somewhat later. Figure 9 shows an example from the clarinet.

Clarinet

Figures 10 to 15 present results obtained from the two clarinet players. In general, the data are quite systematic and reasonably similar for both players, and as can be seen in Tables A1 and A2 in the Appendix, the standard deviations for the *pp-mp-mf* indicate a very consistent behavior of the players. Also, the b_o pressures observed at the start of the *crescendo-diminuendo* tones were very similar to the pp_s values from the sustained tones, see Figures 10 and 11 from player Cl1. The b_p pressures at the peak of the *crescendo* tones are generally close to the mf_s or f_s values of the sustained tones. The termination pressures b_t of the *crescendo-diminuendo* tones are in most cases slightly lower than the b_o at the onset. The pressure ranges from 20 to 55 cm H_2O, and player Cl1 tended to use slightly lower pressures than player Cl2. The loudness increases between the dynamic levels *pp*, *mp* and *mf* correspond to pressure increments. For player Cl1, they range from 3 to 9 cm H_2O for the *pp*, *mp*, and *mf* levels, while for the *ff* level it was up to 15 cm H_2O. Player Cl2 used more even steps, ranging from 3 to 9 cm H_2O.

The blowing pressures measured in the sustained tones agree reasonably well with those observed in the ascending *arpeggio*, the maximum discrepancy being up to 3.0 cm H_2O in *pp* , *mp* and *mf*. In *ff* larger differences were observed. Also, both subjects played sustained tones with pressures quite similar to those they used for the neighbouring tones in the *arpeggio* tasks. There was a quite close agreement between the lowest pressures used for G_4, the common pitch to all three tasks. Thus, the *pp* pressure used in the *arpeggio* (pp_a) was quite similar to the b_o in the *crescendo-diminuendo* tones and also to the p_s in the sustained tones.

Another interesting striking characteristic is the fact that the pressure curve in Figures 14 and 15 exhibit a maximum for all dynamic levels of the *arpeggio*, located at Bb_4. This is probably dependent on the fact that this is the point along the pitch scale where overblowing starts. Thus, the fingering for Bb_4 is identical to that for the lowest pitch Eb_3, except for the opening of the twelfth-key, which produces the overblowing effect.

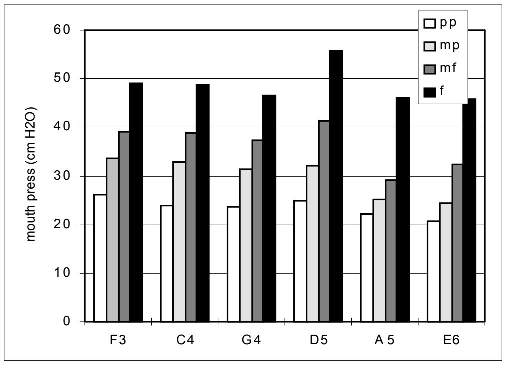

Figure 10. Sustained tones*, player Cl1*

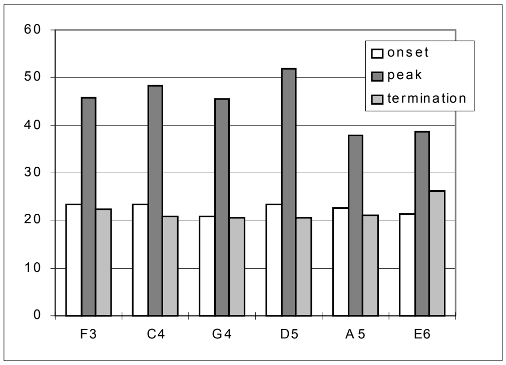

Figure 11. Crescendo-diminuendo*, player Cl1*

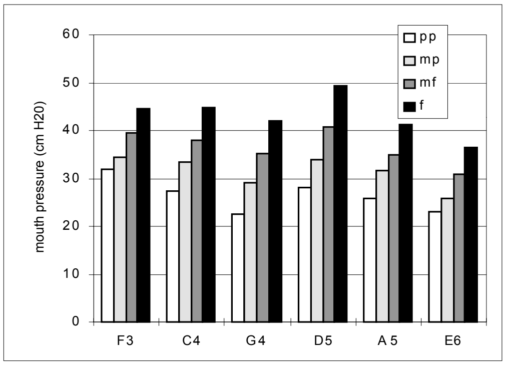

Figure 12. Sustained tones*, player Cl2*

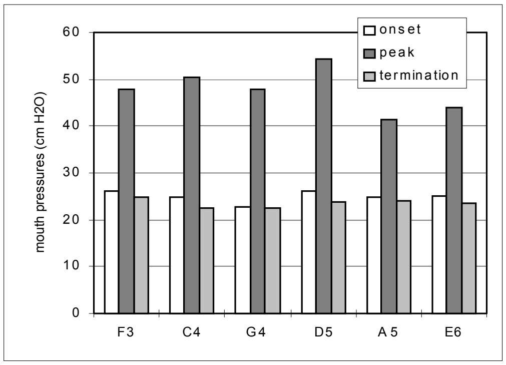

Figure 13. Crescendo-diminuendo*, player Cl2*

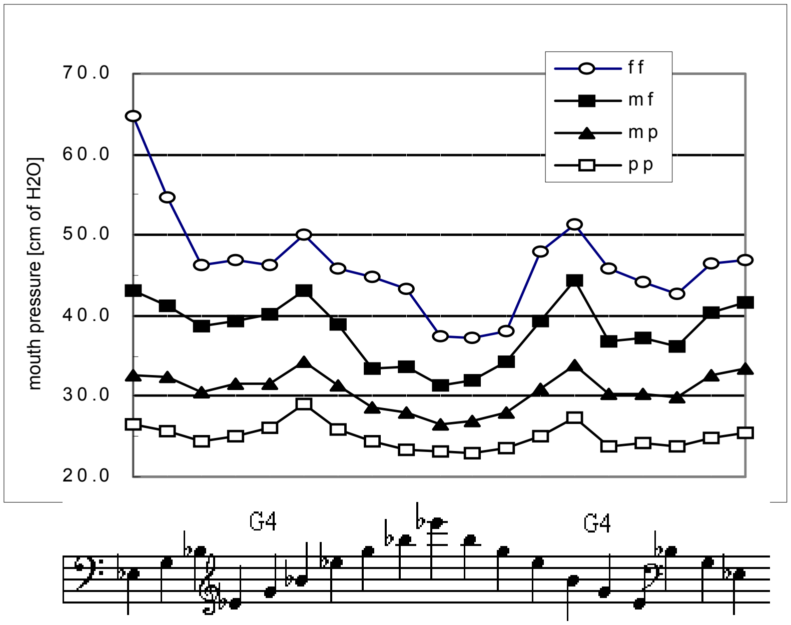

Figure 14. Arpeggio *task , player Cl1.*

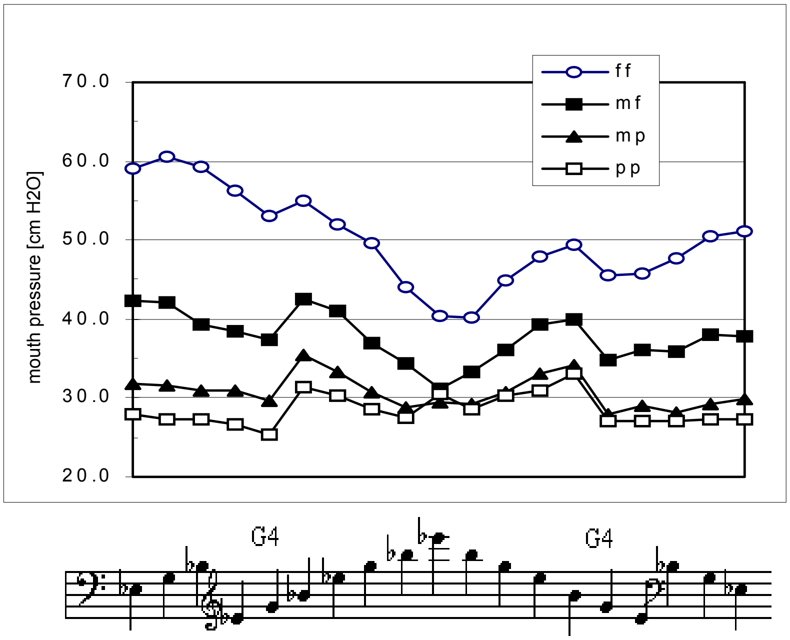

Figure 15. Arpeggio task*, player Cl2.*

Saxophone

Figures 16 to 21 present results obtained from the two saxophone players. The low standard deviations in the *arpeggio* task indicate a good intra-subject consistency, see Tables A3 and A4 in the Appendix. For player Sx1, the pressure ranged from 15 to 80 cm H_2O, approximately. The highest pressure used by player Sx2 was 55 cm H_2O. In general, blowing pressures at low dynamic levels are very close between both players.

As shown in Figures 20 and 21, both players increased pressures when they shifted to a louder dynamic level, except for the lowest pitch, F_3. Player Sx1 regarded the pitches Eb_3 and F_3 as rare tones in symphonic saxophone repertoire; these tones would require a different reed, particularly for soft dynamic levels. This may explain, at least partially, the relatively high pressures for the pitch F_3.

The pressures for Sx1's sustained tones do not agree well with those observed in the *arpeggio* task. However, listening to the recordings and inspecting the SPL values revealed that the sustained tones were played louder than the *arpeggio* tones.

The pressures used for *mf*s**,** sustained tones, agreed closely with the b_p values for all tested tones as played by player Sx2, see figures 18 and 19. Pressure steps between sustained tones played at adjacent dynamic levels are also very regular, ranging approximately from 4.0 to 6.0 cm H_2O.

Comparing the two players, Sx1 tended to use higher pressures in all tasks.

Combining the data from the three tasks from both players, the blowing pressures seem to slightly increase with pitch in the lowest octave of the instrument, reaching a peak in the region between Eb_4 and G_4, and decreasing with pitch above this pitch region. It may be relevant that in the alto saxophone overblowing starts in this pitch range, viz. at F_4.

Oboe

In all tasks, player Ob 2 tended to use considerably higher pressures than player Ob1, particularly at high pitches and high dynamic levels, see Figures 22 to 27. For Ob1 and Ob2, the pressures ranged from 35 to 95 cm H_2O and from 41 to 124 cm H_2O, respectively. In both players, the pressures increased not only with loudness but also with pitch, although the pressure range used by player Ob2 is considerably wider than that used by player Ob1.

In both subjects, the values used for the sustained tones agree quite well with those observed both in the *crescendo-diminuendo* and *arpeggio* tasks. For both players, the onset pressures, b_o, in the *crescendo-diminuendo* task were very close to the pp_s values in the sustained tones, see Figures 22-23 and 24-25. Also, the b_p pressures in the *crescendo* tones were generally close to the mf_s values while the termination pressures b_t were mostly somewhat lower than the b_o. There was a quite close agreement between the lowest pressures used for D$_5$, the pitch common to all three tasks, but the pressure steps between dynamic levels were usually smaller in the *arpeggio* task than in the sustained tones.

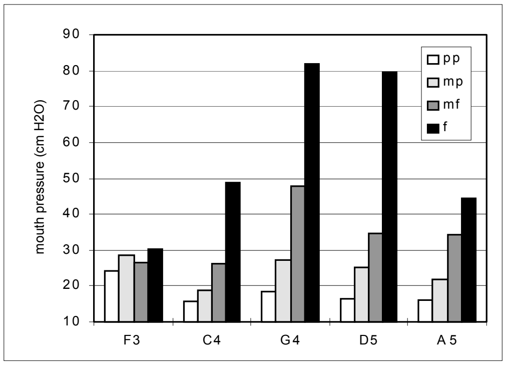

Figure 16. Sustained tones*, player Sx1*

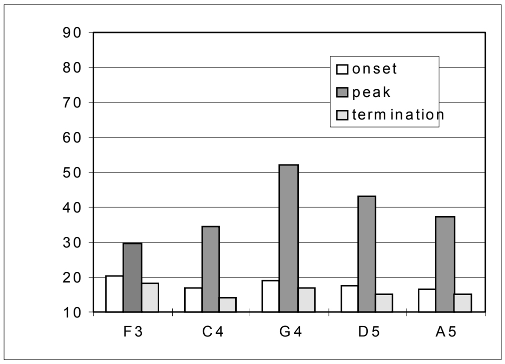

Figure 17. Crescendo-diminuendo*, player Sx1*

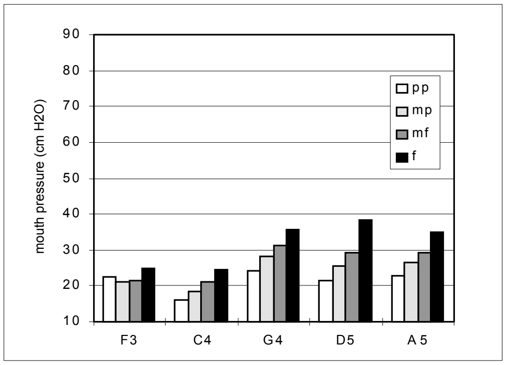

Figure 18. Sustained tones*, player Sx2*

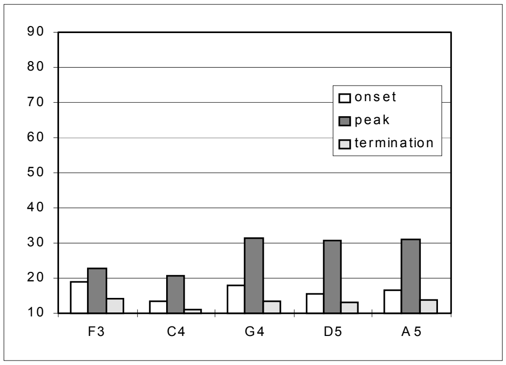

Figure 19. Crescendo-diminuendo*, player Sx2*

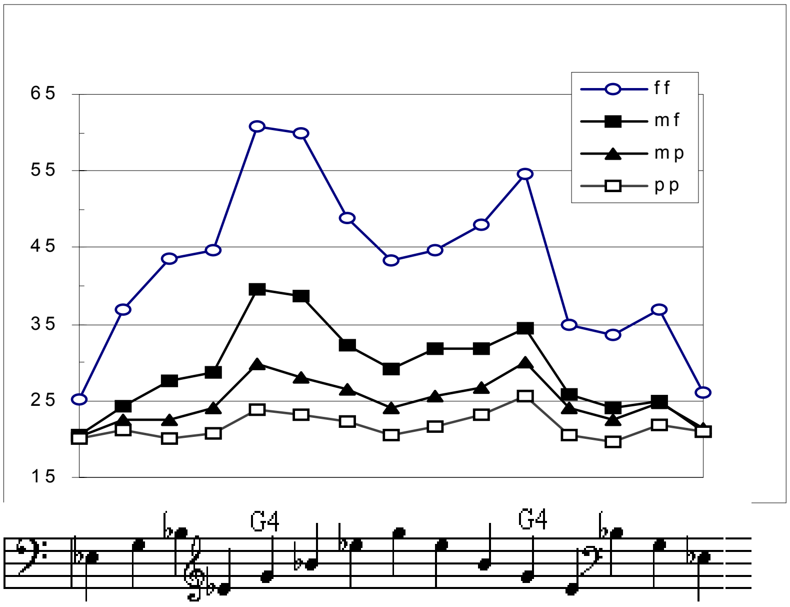

Figure 20. Arpeggio *task , player Sx1*

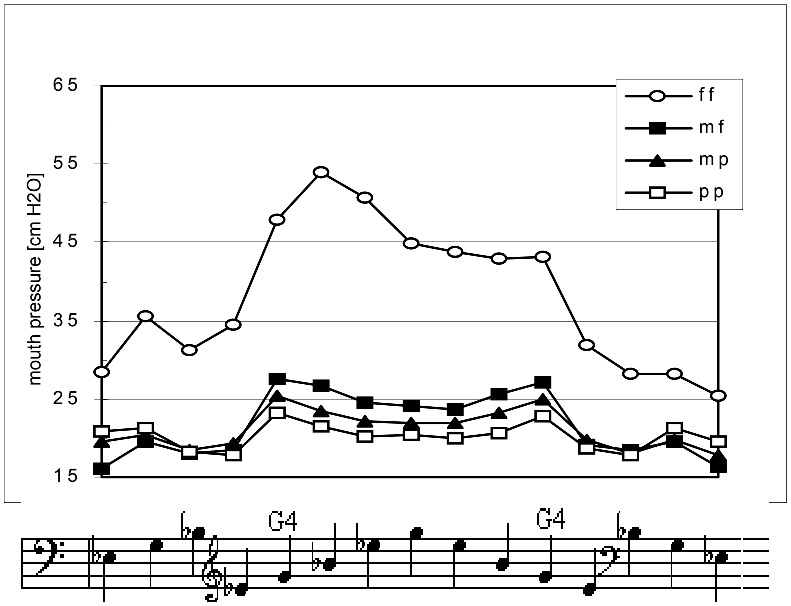

Figure 21. Arpeggio *task, player Sx2.*

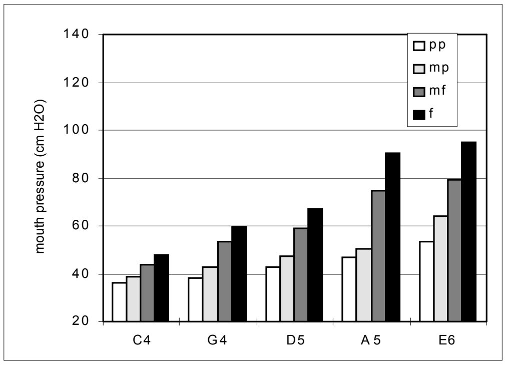

Figure 22. Sustained tones*, player Ob1*

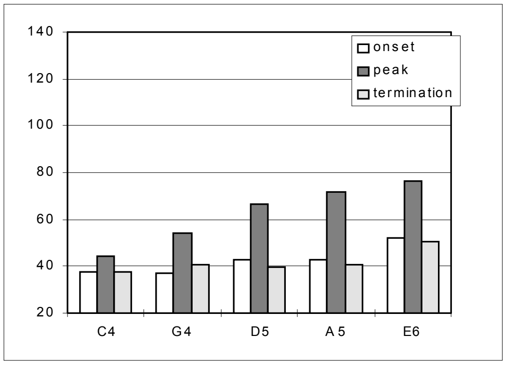

Figure 23. Crescendo-diminuendo*, player Ob1*

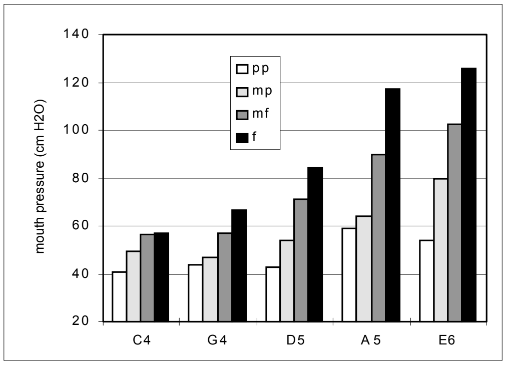

Figure 24. Sustained tones*, player Ob2*

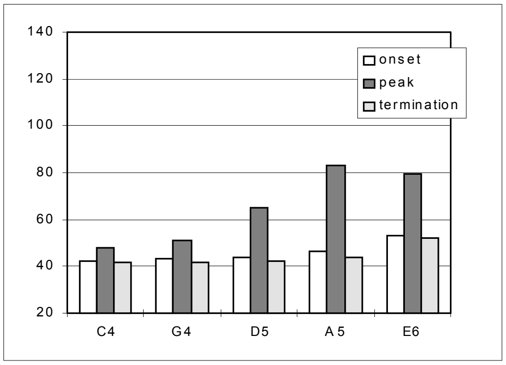

Figure 25. Crescendo-diminuendo*, Player Ob2*

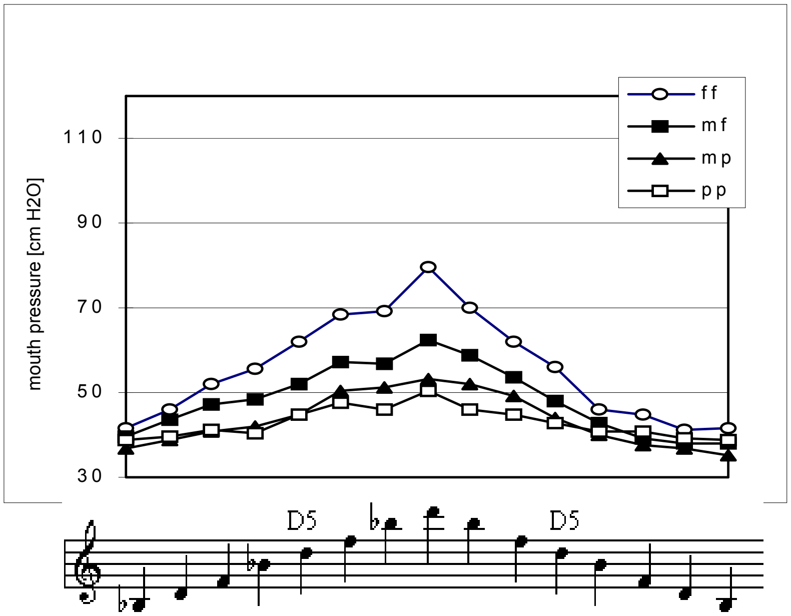

Figure. 26. Arpeggio *task, player Ob1*

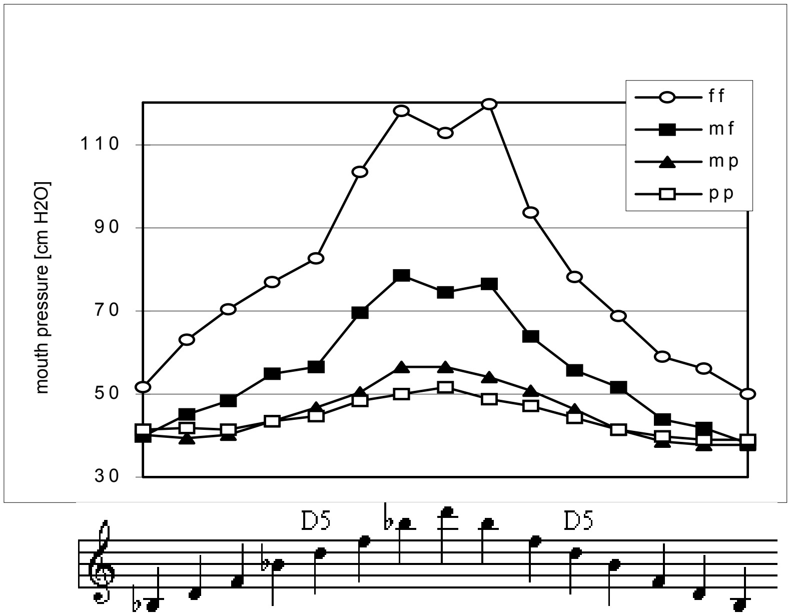

Figure 27. Arpeggio *task, player Ob2*

In the arpeggio task the pressures used for pp and mp were rather similar, especially for the five lowest tones, as seen in Figures 26 and 27. This suggests that at low dynamic levels, the loudness control is mainly realized with other factors than pressure, such as the embouchure. In both subjects, the pressures used for *pp* at the lowest pitches are slightly higher than the ones used for *mp*. The lowest tones of the oboe are particularly difficult to start.

As opposed to the clarinet and the saxophone, the changing of register and the presence of the overblowing effect did not correspond to peaks in the pressure curves.

Bassoon

Figures 28 to 33 present data from the two bassoon players. For players Bn1 and Bn2, the pressure ranged from 12 to 90 cm H_2O and from 13 to 52 cm H_2O, respectively. Tables A7 and A8 (Appendix) show that Bn1's standard deviations mostly ranged from 1 to 3 cm H_2O in *pp-mp-mf* while player Bn2 presents similar ranges for *pp-mp* but at *mf* the standard deviations range from 1 to 5 cm H_2O. Still, all takes from each player sounded musically quite acceptable. Pressure increased continuously with both loudness and pitch. As shown in Figures 28 and 30, the pressure steps between adjacent dynamic levels showed some variation in the sustained tones.

In the *arpeggio,* pressures for *pp* and *mp* were rather similar throughout the pitch range, see Figures 32 and 33, while slightly higher pressures were sometimes used for *pp* than for *mp*.

Looking at sustained tones and *crescendo-diminuendo* tasks from both players, Figures 28-29 and 30-31, the b_o pressures observed at the start of the *crescendo-diminuendo* tones are very similar to the pp_s values from the sustained tones. In a similar way, the b_p pressures at the peak of the *crescendo* tones are generally close to the mf_s or f_s values of the sustained tones. The termination pressures b_t of the *crescendo-diminuendo* tones are in general lower than the b_o at the onset, in a fashion that the difference between b_o and b_t clearly increases with pitch.

At dynamic levels above *pp* both subjects played sustained tones with pressures systematically higher than those used for neighbouring tones in the *arpeggio*. Similarly, pressures used by both subjects for D_3, the pitch common to all three tasks, differed between the arpeggio, a musical context, and the sustained tones, a musically more neutral context. On the other hand, the *pp* pressures in the *arpeggio* (pp_a) were quite similar to the b_o in the *crescendo-diminuendo* tones and also to the p_s in the sustained tones.

As with the oboe, no peculiar characteristic was found relative to the overblowing phenomenon.

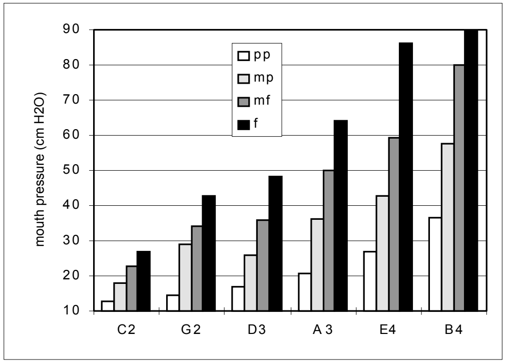

Figure 28. Sustained tones*, player Bn1*

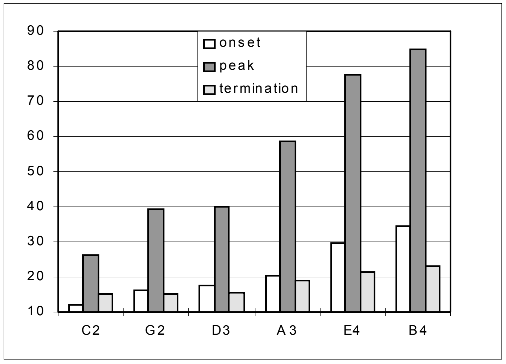

Figure 29. Crescendo-diminuendo*, player Bn1*

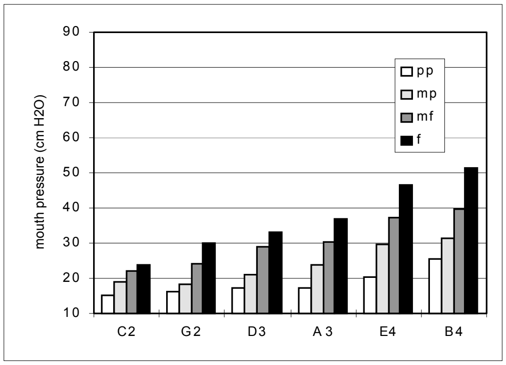

Figure 30. Sustained tones, *player Bn2*

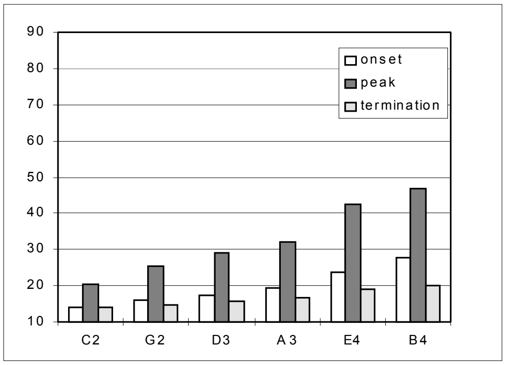

Figure 31. Crescendo-diminuendo*, player Bn 2*

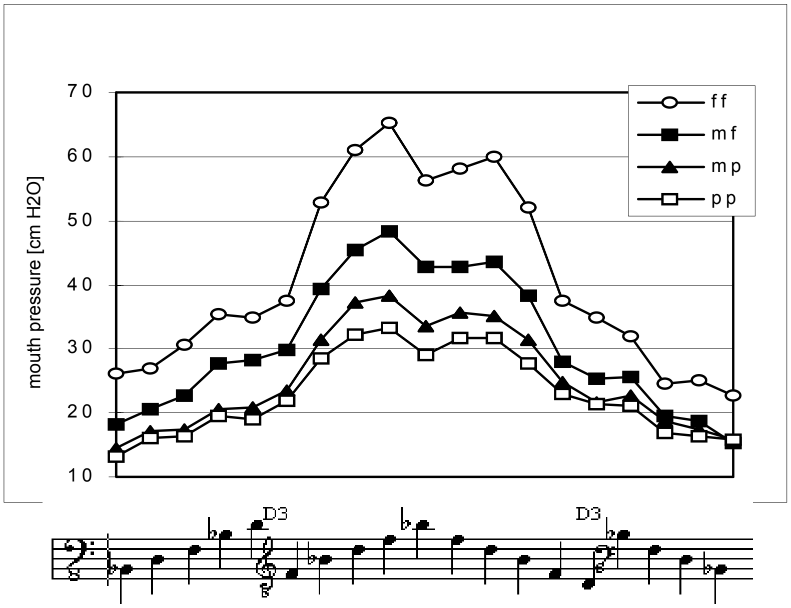

Figure 32. Arpeggio *task, player Bn1*

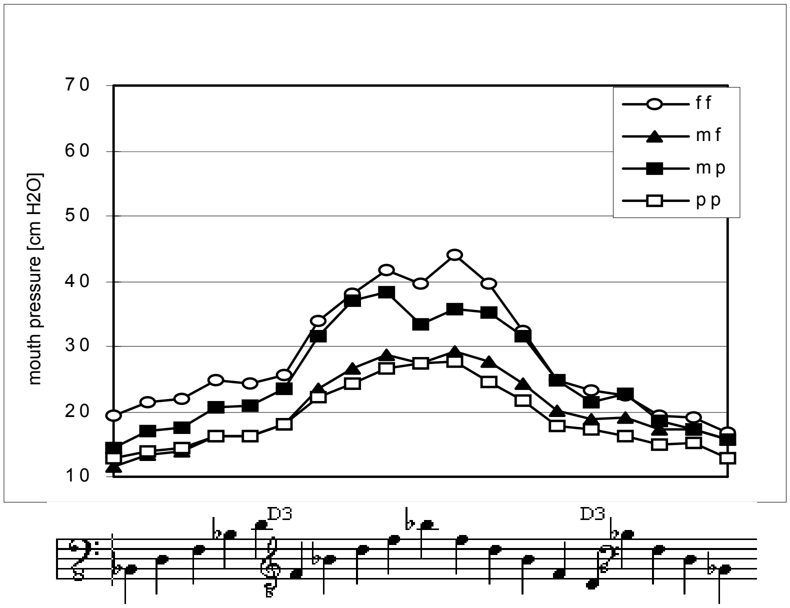

Figure 33. Arpeggio *task, player Bn2*

Discussion

The present investigation was limited to the blowing pressures. These pressures represent a rather special aspect of the overall blowing mechanism. The air flow through the reed and the embouchure conditions are other important aspects, which, however, we will plan to consider in future investigations. The blowing pressures are important to the understanding of the player's work and the instrument behaviour. The air flow is a consequence of the blowing pressure and the resistance offered by the vibrating reed and by the acoustic properties of the air column. The reed system, in turn, is characterized by the geometry and physical properties of the reed, the mouthpiece design and the embouchure.

The data partly agree with those previously reported in the litterature. The pressure ranges observed by Bouhuys (1968) at "low tones" in oboe and clarinet are in reasonable agreement with our results, while his values for "high tones" are clearly higher than those we observed. The pressure ranges for bassoon and clarinet reported by Pawlovski (1985) for numerous subjects (students and professionals) are in reasonable agreement with ours for the clarinet but for the bassoon we observed clearly lower pressures at low pitches. Pawlovski & Zoltowski's (1987) pressure values for identifying good clarinet, oboe and bassoon players do not match our results, which are sometimes much higher and sometimes much lower. On the other hand, our data are in good agreement with the results reported by Fuks (1993) for different loudnesses and pitches played on different reeds by one single professional subject, particularly for the high quality reeds. The systematic dependence on pitch and dynamic level found for the oboe and the bassoon is quite similar to that previously found in singers (Leanderson & al, 1987), although the pressures used in the instrument are obviously much higher.

We tested only two players for each instrument. Mostly both players' pressure data exhibited similar pitch and loudness dependences, but in some cases, noticeably in the oboe and the bassoon, one player tended to consistently use higher pressures than the other. These interindividual differences may be due to different reed properties and/or different blowing techniques and personal preferences.

Clarinets on the one hand and the double reeds oboe and bassoon on the other, showed clearly contrasting features as illustrated particularly by the *arpeggio* curves. In the double reed instruments, pressure tends to be increased continuously with pitch. In the clarinet, pressure tended to decrease with pitch but peaked at the lowest overblowing pitch. These pressure characteristics would be due to the acoustical properties of these instruments, that respond differently depending on their input impedance curves and the reed-instrument interaction. Interestingly, the pressure curves in the lowest octave of the saxophone showed a pattern similar to that of the double reed instruments. However, at higher pitches, where the tones are produced by overblowing, the curves were more similar to those of a clarinet. The saxophone has a conical bore like oboe and bassoon whilst the reed and mouthpiece are similar to those of the clarinet.

In the *arpeggi,* the pressure curves differed between the ascending and descending parts. Generally, higher pressures were used for the ascending part, particularly at the highest dynamic levels. Probably the reason for this was musical; the players tended to make a *crescendo* during the ascending part and a *diminuendo* during the descending part.

The occurrence of higher standard deviations at the *ff arpeggio* in data from most of the subjects may be due to different reasons. One is that playing as loud as possible is an unrealistic task for symphony orchestra musicians, and hence the players would be unfamiliar with such a task.

Both the experimental protocol and the equipment appeared appropriate for our purposes. Ideally, the blowing pressures should be measured for the entire range of the instrument, but this would increase the length of the recording session beyond acceptability. Keeping the pressure transducer in the mouth corner seemed to inflict marginally on the playing.

The refined use of lung pressure in our players raises the question as to the underlying control system. Mechanoreceptors in the subglottal mucosa have been assumed to play an important role in the control of subglottal pressure during phonation (Wyke, 1976). Poor support for this assumption was found in the case of singing (Sundberg et al., 1995). Still, the mechanoreceptors in the subglottal mucosa might play a more prominent role in the control of the considerably higher blowing pressures in wind instruments. There might also be a strong participation of the whole proprioceptive respiratory system, including abdominal, thoracic and lung receptors, on wind instrument players' blowing control that deserves an investigation in the realm of respiratory psychophysics (Katz-Salamon, 1983).

Conclusions

Blowing pressures represent a rather special aspect of the overall blowing mechanism, to which the air flow and embouchure conditions should be added. However, the pressure reflect many aspects of the player's work and the instrument behaviour. Our data have revealed characteristic dependences of the pressure on pitch and on dynamic level in clarinet, saxophone, oboe and basson. For each of these instruments, these dependencies seemed consistent within as well as between players, although some players tended to use higher pressures than others. In the double reed instruments, oboe and bassoon, pressure tends to be increased continuously with pitch. In the clarinet, pressure tended to decrease with pitch, but overblowing was produced with higher pressures than the corresponding lower tones. The pressure curves in the lowest octave of the saxophone showed a pattern similar to that of the double reed instruments. However, at higher pitches, where the tones are produced by overblowing, the curves were more similar to those of a clarinet.

Acknowledgements

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Appendix

A. Mouth pressure data tables from *arpeggio* task

Table A1. Mean and standard deviations of mouth pressures in cm of water, player Cl1

		Eb3	**G3**	**Bb3**	**Eb4**	**G4**	**Bb4**	**Eb5**	**G5**	**Bb5**	**Eb6**	**Bb5**	**G5**	**Eb5**	**Bb4**	**G4**	**Eb4**	**Bb3**	**G3**	**Eb3**
ff	mean	65	55	46	47	46	50	46	45	43	37	37	38	48	51	46	44	43	46	47
	stdev	4.5	3.7	3.3	2.3	2.4	1.9	2.0	4.1	2.2	4.4	1.3	2.9	3.0	4.5	4.9	2.9	2.9	2.9	6.3
mf	mean	43	41	39	39	40	43	39	33	34	31	32	34	39	44	37	37	36	40	42
	stdev	2.6	0.8	1.2	0.9	1.7	2.6	2.3	1.8	1.6	3.0	1.2	2.0	0.5	3.3	2.0	1.0	1.1	2.0	1.7
mp	mean	33	32	30	32	32	34	31	29	28	26	27	28	31	34	30	30	30	33	33
	stdev	1.7	1.2	0.9	0.4	1.1	0.7	0.5	0.8	0.9	1.0	0.8	0.6	0.7	0.7	0.2	0.5	0.6	1.0	1.5
pp	mean	26	26	24	25	26	29	26	24	23	23	23	24	25	27	24	24	24	25	26
	stdev	1.0	1.4	1.3	1.4	1.2	1.6	1.2	1.0	0.8	0.5	0.8	0.9	0.8	1.0	0.9	0.3	0.7	0.4	0.5

Table A2. Mean and standard deviations of mouth pressures in cm of water, player Cl2

		Eb3	**G3**	**Bb3**	**Eb4**	**G4**	**Bb4**	**Eb5**	**G5**	**Bb5**	**Eb6**	**Bb5**	**G5**	**Eb5**	**Bb4**	**G4**	**Eb4**	**Bb3**	**G3**	**Eb3**
ff	mean	59	60	59	56	53	55	52	50	44	40	40	45	48	49	46	46	48	50	51
	stdev	0.7	3.8	4.1	3.0	2.7	3.9	3.3	0.7	1.1	2.5	1.4	2.8	2.2	2.1	1.8	1.9	4.8	3.6	1.2
mf	mean	42	42	39	38	37	43	41	37	34	31	33	36	39	40	35	36	36	38	38
	stdev	1.0	1.6	2.1	2.0	1.9	2.3	1.5	1.4	1.6	1.4	0.7	1.0	1.5	0.6	1.3	1.2	1.2	2.0	2.9
mp	mean	32	32	31	31	30	35	33	31	29	29	29	31	33	34	28	29	28	29	30
	stdev	2.2	2.8	1.8	0.8	0.7	0.3	0.8	0.8	0.5	1.5	0.6	0.3	0.6	0.7	0.3	0.3	1.1	1.1	1.9
pp	mean	28	27	27	27	25	31	30	29	27	31	29	30	31	33	27	27	27	27	27
	stdev	1.3	1.6	1.7	0.8	0.7	0.5	0.7	0.4	0.7	0.5	0.8	1.0	0.4	0.9	0.5	0.9	0.7	0.6	0.6

Table A3. Mean and standard deviations of mouth pressures in cm of water, player Sx1

		Eb3	**G3**	**Bb3**	**Eb4**	**G4**	**Bb4**	**Eb5**	**G5**	**Eb5**	**Bb4**	**G4**	**Eb4**	**Bb3**	**G3**	**Eb3**
ff	mean	25	37	43	45	61	60	49	43	45	48	55	35	34	37	26
	st.dev.	1.2	3.5	4.6	1.9	4.7	5.0	4.2	5.4	4.2	2.5	4.5	2.4	5.3	2.6	1.3
mf	mean	21	24	28	29	40	39	32	29	32	32	35	26	24	25	21
	st.dev.	0.6	1.4	2.1	1.2	1.6	1.8	2.6	1.7	2.8	3.0	4.9	3.2	2.7	2.8	1.5
mp	mean	20	23	22	24	30	28	26	24	26	27	30	24	23	25	21
	st.dev.	0.2	0.5	0.3	0.7	1.1	1.3	1.0	1.4	1.3	1.3	2.0	1.1	1.1	0.8	0.4
pp	mean	20	21	20	21	24	23	22	21	22	23	26	21	20	22	21
	st.dev.	0.4	0.1	0.2	0.3	0.9	0.6	0.6	0.9	1.0	0.6	0.8	0.3	0.4	0.5	0.3

Table A4. Mean and standard deviations of mouth pressures in cm of water, player Sx2

		Eb3	**G3**	**Bb3**	**Eb4**	**G4**	**Bb4**	**Eb5**	**G5**	**Eb5**	**Bb4**	**G4**	**Eb4**	**Bb3**	**G3**	**Eb3**
ff	mean	28	36	31	34	48	54	51	45	44	43	43	32	28	28	25
	stdev	1.2	1.2	0.8	1.6	1.0	2.1	1.6	0.5	0.4	0.4	0.5	0.6	0.7	1.9	3.9
mf	mean	16	19	18	19	28	27	25	24	24	26	27	19	18	20	16
	stdev	1.2	0.2	0.5	0.6	0.9	0.3	0.3	0.7	0.3	0.3	0.5	0.8	0.4	0.8	0.3
mp	mean	19	20	18	19	25	24	22	22	22	23	25	20	18	20	18
	stdev	2.3	0.8	0.9	1.1	1.4	1.4	1.0	0.7	0.9	1.1	1.1	0.8	1.0	0.7	0.8
pp	mean	21	21	18	18	23	22	20	20	20	21	23	19	18	21	20
	stdev	0.6	1.9	1.2	0.6	1.5	1.3	1.1	0.7	1.4	1.2	1.3	0.9	0.6	0.9	0.7

Table A5. Mean and standard deviations of mouth pressures in cm of water, player Ob1

		Bb3	D4	F4	Bb4	D5	F5	Bb5	D6	Bb5	F5	D5	Bb4	F4	D4	Bb3
ff	mean	41	46	52	56	62	68	69	80	70	62	56	46	45	41	42
	stdev	3.6	5.1	5.3	1.9	5.8	9.5	7.3	4.7	3.7	6.3	8.1	5.9	4.8	3.8	3.7
mf	mean	40	43	47	48	52	57	57	62	59	54	48	43	39	38	38
	stdev	1.8	2.8	5.9	3.8	2.7	3.3	3.1	1.5	2.8	2.1	1.6	1.0	1.2	1.4	1.4
mp	mean	37	39	41	42	45	50	51	53	52	49	44	40	38	37	35
	stdev	1.1	2.0	0.7	0.4	0.5	1.2	2.9	3.1	1.9	1.5	1.3	0.6	0.6	1.3	1.3
pp	mean	39	40	41	41	45	48	46	50	46	45	43	41	41	39	39
	stdev	2.1	2.5	2.3	0.5	3.7	1.9	1.9	1.5	0.9	1.2	1.6	1.5	0.7	1.1	1.2

Table A6. Mean and standard deviations of mouth pressures in cm of water, player Ob2

		Bb3	D4	F4	Bb4	D5	F5	Bb5	D6	Bb5	F5	D5	Bb4	F4	D4	Bb3
ff	mean	52	63	70	77	82	103	118	113	120	94	78	69	59	56	50
	stdev	3.0	2.5	2.3	3.5	6.0	7.6	5.9	7.8	4.3	3.3	3.6	4.3	2.9	4.8	3.0
mf	mean	40	45	48	55	57	70	78	74	76	64	56	52	44	42	38
	stdev	1.4	1.7	1.8	2.0	1.8	1.8	2.0	2.5	2.2	2.4	2.1	1.7	0.7	1.0	0.5
mp	mean	40	39	40	43	47	50	57	56	54	51	46	41	39	38	38
	stdev	1.6	2.3	2.4	2.1	2.2	3.5	4.6	4.5	3.1	2.2	1.8	1.7	1.1	0.9	1.0
pp	mean	42	42	41	43	45	48	50	51	49	47	44	41	40	39	39
	stdev	1.7	2.3	1.7	2.5	2.3	2.3	2.6	1.4	0.7	1.0	0.4	0.8	1.1	0.7	1.1

Table A7. Mean and standard deviations of mouth pressures in cm of water, player Bn1

		Bb1	D2	F2	Bb2	D3	F3	Bb3	D4	F4	Bb4	F4	D4	Bb3	F3	D3	Bb2	F2	D2	Bb1
ff	mean	26	27	31	35	35	37	53	61	65	56	58	60	52	37	35	32	25	25	23
	stdev	1.4	1.5	1.1	1.3	2.0	3.3	1.8	3.6	2.4	5.1	3.3	4.0	3.0	1.8	3.1	0.3	1.2	2.3	1.4
mf	mean	18	21	23	28	28	30	39	45	48	43	43	44	38	28	25	26	20	19	15
	stdev	0.7	0.7	0.6	1.1	1.2	1.0	1.3	1.4	1.3	1.1	1.0	0.9	1.1	0.8	1.0	0.8	0.5	0.2	0.7
mp	mean	15	17	17	21	21	24	31	37	38	33	36	35	31	25	22	23	19	17	16
	stdev	0.6	0.6	2.0	1.5	1.9	2.1	0.7	1.4	1.6	1.3	2.2	1.1	1.2	1.1	0.8	0.4	1.3	0.6	1.0
pp	mean	13	16	16	19	19	22	28	32	33	29	32	32	28	23	21	21	17	16	16
	stdev	0.8	1.1	0.5	0.9	1.7	1.4	0.4	1.0	0.7	1.2	2.0	2.3	1.3	1.4	2.0	3.0	1.4	1.2	0.7

Table A8. Mean and standard deviations of mouth pressures in cm of water, player Bn2

		Bb1	D2	F2	Bb2	D3	F3	Bb3	D4	F4	Bb4	F4	D4	Bb3	F3	D3	Bb2	F2	D2	Bb1
ff	mean	19	21	22	25	24	26	34	38	42	40	44	40	32	25	23	23	19	19	17
	stdev	1.0	1.0	0.7	0.4	0.4	1.4	2.3	1.8	1.9	3.0	1.5	1.4	2.0	1.9	1.3	0.7	0.5	0.9	1.3
mf	mean	12	13	14	16	16	18	23	27	29	27	29	28	24	20	19	19	17	17	16
	stdev	0.3	0.4	0.9	1.3	0.2	1.0	1.0	2.1	4.9	4.1	3.7	2.7	4.4	2.5	3.0	2.2	1.3	0.7	0.7
mp	mean	15	17	17	21	21	24	31	37	38	33	36	35	31	25	22	23	19	17	16
	stdev	0.8	1.1	1.2	0.9	0.9	1.1	2.0	0.9	0.5	1.9	1.5	2.3	2.3	2.5	1.7	1.4	1.4	0.8	0.7
pp	mean	13	14	14	16	16	18	22	24	27	27	28	25	22	18	17	16	15	15	13
	stdev	0.5	0.8	0.9	0.9	0.6	0.9	2.9	1.8	2.3	1.1	1.7	2.3	1.4	0.8	0.7	0.7	0.9	0.9	0.9

B. Specifications of the instruments

Table B1. Instruments brands, reeds and mouthpiece according to player

Player	Instrument	Reed	Mouthpiece
Cl1	Buffet-Crampon Prestige	Vandoren 3.5	Vandoren B40
Cl2	Buffet-Crampon Prestige	Glotin 3.5	James Canter
Sx1	Yamaha YAS855 Custom	Glotin 3.5	Vandoren A28
Sx2	Yamaha Super Action II	Vandoren 3.5	Selmer C*
Ob1	Marigaux Conservatoire	hand-made	
Ob2	Joseph , German System	hand-made	
Bn1	Fox Professional series TL	hand-made	
Bn2	Heckel, Austrian System	hand-made	

Aerodynamic input parameters and sounding properties in naturally blown reed woodwinds

Leonardo Fuks

Abstract

Input aerodynamic parameters in reed woodwinds - oboe, alto saxophone, bassoon and clarinet - were measured when professionals played different pitches at three dynamic levels. Two reeds were used, one rated as a hard and another as a soft reed. The tasks consisted of playing long sustained tones with and without vibrato. Audio and blowing pressure signals were recorded. Lung volume variations were indirectly measured by a spirometric procedure, which also showed the average air consumption, i.e. the mean airflow. The tones were played in a laboratory room and also in a calibrated reverberant chamber allowing estimation of radiated sound power. Average values for flow resistance, aerodynamical power and mechanical efficiency were computed. Airflow and input power varied considerably between instruments and between the two reed types, but generally increased with sound level. For vibrato tones produced on oboe, bassoon and saxophone, wide pressure oscillations were observed, on average 10 cm H_2O for the oboe and bassoon, and reaching values of 20 cm H_2O in some cases. Possible origins of these pressure variations are discussed.

Introduction

A wind instrument may be seen as a device that converts aerodynamical into acoustical energy. During this process, just a minute portion of the input energy is converted into sound, usually less than 1% (Benade & Gans, 1968; Fletcher & Rossing, 1998). Nonetheless, our sense of hearing is compatible with the dynamic range produced by these instruments. For a given fingering configuration in reed instruments, the two main input parameters are blowing pressure and embouchure. However, there may be considerable variability in the instrument/reed design, the reed's mechanical properties, the adjustments of the lips, the responsiveness of the instrument and the technique used.

There are several reasons why the blowing pressure is an essential input parameter. One is that reed woodwinds are pressure-controlled systems (Benade & Gans, 1968). This implies that the pressure controls the reed vibration and hence the major acoustic characteristics of the tone, such as fundamental frequency, amplitude, and spectrum. Therefore, wind players possess a fine control over the pressure parameter, as confirmed in previous investigations (Smith et al., 1990; Fuks & Sundberg, 1996; Fuks, 1998).

Airflow in a given woodwind instrument is the result of the specific combination of blowing pressure, design and mechanical properties of the reed, and embouchure. In addition, the responsiveness of the instrument bore contributes.

Airflow has been measured and/or estimated in previous studies (Bouhuys, 1964, 1965; Pawlowsky & Zoltowski, 1985, 1987; Fuks, 1995; Fuks & Sundberg, 1998). These studies showed that the flow tends to increase with increasing amplitude but varies between instruments. However, the experimental data available do not clearly describe the relationship between airflow, blowing pressures and sounding parameters of realistically produced sounds. A main problem in airflow measurement in wind instruments derives from the fact that most available methods significantly affect the instrument and/or the player's behaviour. To circumvent the latter problem, artificial embouchures and blowing systems have been used (Meynial, 1987; Gilbert, 1991; Idogawa et al., 1993; Gazengel, 1994). These systems provide robust, accurate and highly consistent data. On the other hand, they have the limitation of not necessarily reproducing realistic playing conditions.

The aim of the present study was to assemble realistic data on the relationship between input parameters and some acoustical properties of woodwind instruments by measuring blowing pressure, sound pressure level and airflow rate in long, steady tones and in vibrato tones.

Material and methods

The subjects, all having more than 10 years of continuous practice on the instruments, played the oboe, saxophone, bassoon or clarinet. Two contrasting reeds were used for each instrument, one rated by the player as soft and one as hard. The instruments are specified in the Appendix, Table 2. Test tones, specified in Table 1, consisted of sustained tones at *pp* (the softest possible continuous sound), *mf* (a comfortable loud sound) and *ff* (the loudest possible sound) played with no vibrato and with vibrato.

As an initial training program, the subjects produced maximal inhalations in a standing position immediately followed by 30 seconds of constant blowing through a calibrated airflow resistor (R=0.359 cm H_2O.s/ml) at a pressure of 30 cm H_2O. Mouth pressure was measured by means of a pressure transducer (Gaeltec 7Sb) connected to the upstream side of the resistor hose. The transducer's amplifier provided visual feedback of the readings. Immediately after the exhalatory phase, the subjects inhaled through the pneumotachometer mouthpiece (Silverman-Lilly type, Mercury CS-5, F100L flowhead) back to full lungs. The expected volume blown through the resistor under these conditions was 2510 ml, approximately. This initial training program also served to evaluate the subjects' consistency in starting the playing task from a high lung volume level. In general, the subjects presented deviations of less than 150 ml for the fixed flow procedure, i.e. about 6%.

After this training, the subjects sustained the test tones mentioned above as long as possible, keeping a constant blowing pressure. This procedure is similar to the one used by Bouhuys (1964), with the difference that he measured the remaining air volume with a spirometer while the subjects exhaled after playing the tones. We preferred to have the subjects play at a fixed pressure as long and as stable as possible, and then to inhale through the meter mouthpiece. The audio signal was recorded on a DAT Casio DA-7. A multichannel TEAC (RD-200T) PCM DATA recorded the output signals from the pneumotachometer, the pressure transducer and the sound level meter. For analysis, all recordings were converted into the SMP Swell format (Nyvalla AB, Sweden). All air volume measurements refer to a room temperature of 20°C and 40% relative humidity.

Two or three similar takes of each test tone were obtained. For each tone and dynamic level the blowing pressure and sound pressure level of the first valid take were measured. The subjects' task was then to replicate these measured values in the subsequent repeats of this tone, using visual feedback from the equipment. In this manner, a similar production was secured for the repeats.

In addition a vibrato version was recorded of each test tone on the oboe, saxophone and bassoon; clarinet vibrato is not commonly used in the classical tradition although it does occur in pop and jazz styles, and also in contemporary music (Rehfeldt, 1994). From these recordings oscillations of blowing pressure and other parameters associated with the production of vibrato tones could be studied. For the vibrato tones, the subjects were instructed to produce an intense, though musically acceptable vibrato. A vibrato may be produced by different mechanisms, which may be combined (Gärtner, 1973). According to the jargon used by professional players it can be produced by "wind", "throat" or "lip" oscillation. The "wind" type of vibrato would be mainly generated by variations in the blowing pressure. In the experiment, the players were asked to use the last mentioned alternative. Just one take was made for each test tone and dynamical level.

Table 1. Test tones used in the experiment, both for sustained and vibrato tones. Note names refer to the sounding pitch (orchestral pitch), rather than to the instrumental name.

Instrument	**Test tones**
Oboe	C_4 E_5 D_6
Clarinet	D_3 Bb_3 F_5 E_6
Alto saxophone	Eb_3 G_4 F_5
Bassoon	Bb_1 D_3 C_4 A_4

The recordings were made in a laboratory room using a sound-level meter microphone (Ono Sokki LA-210, A-weighting mode) that was placed at 2.0 m distance from the player, 1.5 m above the floor and at a 90° angle to the floor. The tone duration and the concomitant air volume were measured for each take.

After this task was completed, which took approximately 1.5 hours for each instrument, the players were taken to a calibrated reverberant chamber with 113.32 m^3 volume (V_r) and 6.4 seconds reverberation time (T_r). The same test tones and blowing pressures were repeated there, although the tones were sustained for at least 20 seconds. For tones requiring high airflow, the players were allowed to restart the tone after a brief breath pause, so that a stable maximal level could be achieved. In this way, the reverberation sound level could be determined with the SPL meter, which was set to a flat frequency curve. The purpose of this recording was to measure the full spectrum produced, without effects of the directivity characteristics or the absorption of partials, which can be expected in an ordinary room or in an anechoic chamber. The reason for not carrying out the whole experiment in the reverberation room was the high sound pressure levels produced. Also the subjects' unfamiliarity with the abundant reverberation could be expected to lead to an atypical playing behaviour.

The SPL meter was calibrated with a standard sound source (B&K 4230), with a 1000 Hz tone at 94 dB. The pneumotacograph was calibrated by means of a 2000 ml cylinder, with inspiratory flow.

Analysis

Sustained tones

SPL (in dBA at the lab and dB at the reverberant chamber), playing time, estimated lung volume decrease, and blowing pressure were determined from the recordings according to Equations 1-4.

Resistance across the reed was calculated as

$$R = \frac{P_{mouth}}{\dot{V}} \qquad \text{Equation 1}$$

where, R is average resistance in cm $H_2O \cdot s/ml$

P_{mouth} is blowing pressure in cm H_2O

$\dot{V}$ is mean airflow, in ml/s calculated as estimated lung volume decrease over playing time.

Mechanical power delivered to the air, W_a, was calculated in watt from

$$W_a = k_1 . P_{mouth} . \dot{V} \,, \qquad \text{Equation 2}$$

k_1 is a conversion coefficient $9.8 \cdot 10^{-5}$,

Sound power in the reverberant room, P_r, in watts, was calculated as

$$P_r = \frac{I_{rev} . V_r}{36 . T_r} \qquad \text{Equation 3}$$

$$I_{rev} = 10^{\frac{SPL}{10}} . 10^{-12} \qquad \text{Equation 4}$$

where, I_{rev} is sound intensity in the reverberant chamber, calculated from the SPL_{rev}

V_r is the volume of the reverberant chamber (133.35 m^3)

T_r is the reverberation time in the chamber (6.4 seconds)

Efficiency, in %, is calculated as the ratio between P_r and W_a.

Vibrato tones

The audio and pressure signals during the vibrato tones, in the SMP format, were processed in Soundswell program (Nyvalla AB, Sweden), by means of which the fundamental frequencies were extracted. For computation of the sound pressure level variations, the Extract program was used (Nyvalla AB, Sweden). The vibrato parameters, i.e. P_{mouth} variation (ΔP_{mouth}), vibrato extent and amplitude modulation, were averaged from a fragment of approximately 2 seconds in each example (Figure 5). ΔP_{mouth} reflect the mean difference between maximum and minimum pressures, cycle by cycle, while vibrato extent and amplitude modulation refer to the ±amplitude of the sound undulations, expressed in cents and dB, respectively.

Results

Sustained steady tones

The raw data (dynamic level, SPL_{room}, SPL_{rev}, P_{mouth}) and the parameters derived from them (mean flow, resistance, mechanical power, sound power and efficiency) are presented in the Appendix in Tables 3-6 for oboe, clarinet, saxophone and bassoon, respectively. Figures 1-4 show a selection of the data in graphical form.

In general, the blowing pressures were in good agreement with those previously reported for reed woodwinds (Fuks & Sundberg, 1996). The values for hard reeds were consistently higher than for soft reeds. This supports the assumption that the blowing pressure required is one of the main parameters for deciding if a reed is perceived as hard or soft.

The SPL_{rev}, which takes into consideration all frequency components in the entire spectrum, showed considerably differing values as compared to the SPL_{room}. This is not surprising, since the directional properties of the instruments are complex and differ between notes, microphone position and other factors (Meyer, 1966; Jansson, 1976). The SPL values and the associated blowing pressures were also systematically higher for hard reeds than for soft reeds, indicating that the threshold pressures were higher, but also that hard reeds would be able to produce louder tones (Grand et al., 1996).

The effective dynamic range, i.e. the difference between SPL at *ff* and *pp* varied according to instruments. In the oboe, saxophone and clarinet, the dynamic range was generally higher for the hard reed. In the bassoon, the dynamic range for the hard reed tended to be higher for the two lowest tones (Bb_1, D_3), and lower for the high tones.

In almost all cases the airflow values increased with dynamic level, for both reed types. Also, the hard reeds presented systematically higher blowing pressures, higher airflow and higher mechanical power than the soft reeds, for the same test tones.

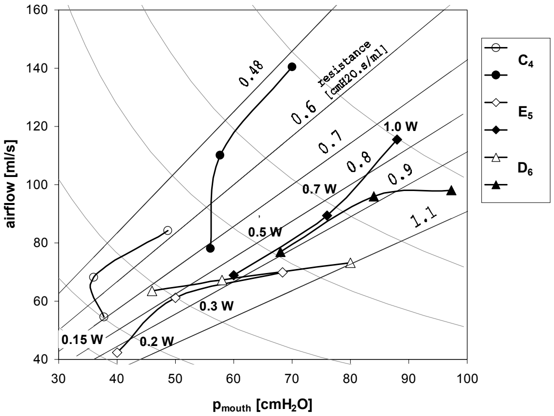

Figure 1. Pressure and flow data for oboe for tones C_4 , E_5 and D_6 . Connected points refer to pp, mf and ff; generally, P_{mouth} and airflow increase between these 3 dynamic levels. The straight oblique lines represent constant flow resistance, while the hyperbolic curves refer to points of constant input mechanical power. Open and filled symbols refer to soft and hard reed, respectively.

Oboe

Figure 1 shows the relationships between mouth pressure, airflow, resistance and mechanical power. Blowing pressures ranged between 36-97 cm H_2O for the test tones and mean airflow between 42-140 ml/s. The flow resistance varied between 0.50 and 1.09 cm H_2O·s/ml, the mechanical power between 0.17-1.00 watt and the estimated sound power radiated between 0.20-15.55 mwatt. As a consequence, the mechanical efficiency varied between 0.01% and 1.56%.

For each reed, blown at the *mf* level, airflow did not vary considerably with respect to pitch, 61-67 ml/s for the soft and 89-110 ml/s for the hard reed. In almost all cases, airflow had a positive correlation with blowing pressure and dynamical level. The hard reed produced higher sound power than the soft reeds, at a given dynamical level. However, the values for flow resistance were comparable between hard and soft reeds, for each test tone. In all cases, the mechanical efficiency increased with dynamical level, for a given test tone.

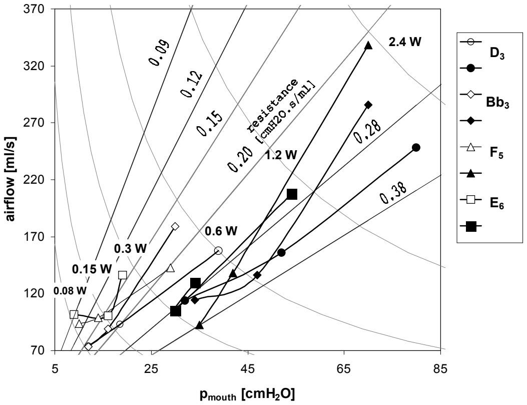

Figure 2. Pressure and flow data for Bb clarinet for tones D_3 , Bb_3 , F_5 and E_6 . Connected points refer to pp, mf and ff; generally, P_{mouth} and airflow increase between these 3 dynamic levels. The straight oblique lines represent constant flow resistance, while the hyperbolic curves refer to points of constant input mechanical power. Open and filled symbols refer to soft and hard reed, respectively.

Clarinet

As shown in Figure 2, blowing pressures ranged between 9-80 cm H_2O and airflow between 74-338 ml/s. The flow resistance varied between 0.09 and 0.38 cm H_2O.s/ml, the mechanical power between 0.09-2.32 watt, and the sound power between 0.01-6.19 mwatt. Mechanical efficiency varied between 0.003% and 1.84%.

Airflow at *mf* varied between 89-156 ml/s for both reeds. In almost all cases, airflow had a positive correlation with blowing pressure and dynamic level. As in the oboe, the hard reeds generated higher sound power at a given dynamical level than the soft reeds. In addition, the values for flow resistance were consistently higher for the hard as compared to the soft reed. With the exception of the E_6 test tone, efficiency tended to be higher for the soft reed at comparable pitch and dynamical level.

Alto saxophone

As shown in Figure 3, blowing pressures ranged between 20-70 cm H_2O while airflow varied widely, between 61-917 ml/s. Flow resistance ranged between 0.05 and 0.51 cm H_2O.s/ml, mechanical power between 0.12-3.60 watt and the estimated sound power between 0.25-39.07 mwatt. As a consequence, the mechanical efficiency varied between 0.076% and 4.116%. Interestingly, mouth pressure remained essentially constant for the three dynamic levels in the case of tone Eb$_4$ blown with the hard reed, while airflow varied considerably.

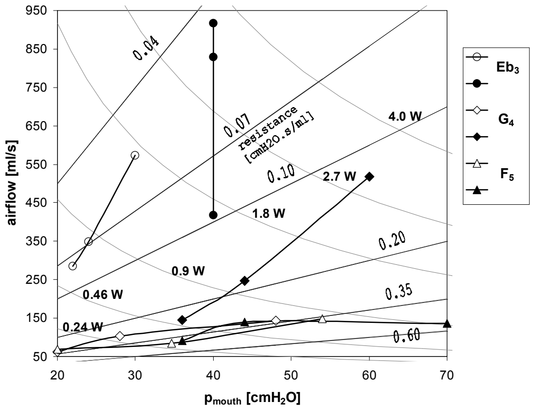

Figure 3. Pressure and flow data for alto saxophone for tones Eb$_3$, G$_4$, and F$_5$.. Connected points refer to pp, mf and ff; generally, P$_{mouth}$ and airflow increase between these 3 dynamic levels. The straight oblique lines represent constant flow resistance, while the hyperbolic curves refer to points of constant input mechanical power. Open and filled symbols refer to soft and hard reed, respectively.

Airflow at *mf*, considering the two reeds, varied between 85-830 ml/s. In almost all cases, airflow had a positive correlation with blowing pressure and dynamical level. Also, the values for flow resistance were comparable for hard and soft reeds. At a given pitch and dynamical level efficiency tended to be higher with the soft reed.

Bassoon

Blowing pressures and airflow for the test tones ranged between 21-74 cm H$_2$O and 75-597 ml/s respectively (Figure 4). Flow resistance varied between 0.08 and 0.53 cm H$_2$O.s/ml, mechanical power between 0.25-2.69 watt, and the estimated sound power between 0.08-7.79 mwatt. The resulting mechanical efficiency varied between 0.024% and 1.14%.

Airflow at *mf* varied between 126-350 ml/s. In almost all cases, airflow had a positive correlation with blowing pressure and dynamical level. However, for test tones C$_4$ and A$_4$, the highest ones, the airflow did not change greatly with dynamical level. With the exception of note C$_4$, the values for flow resistance were very similar among hard and soft reeds. Efficiency varied considerably among hard and soft reeds, but tended to increase with loudness for both types of reeds.

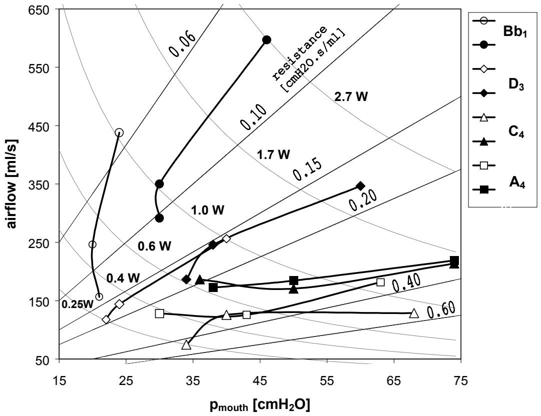

Figure 4. Pressure and flow data for bassoon for tones Bb$_1$, D$_3$, C$_4$ and A$_4$. Connected points refer to pp, mf and ff; generally, P$_{mouth}$ and airflow increase between these 3 dynamic levels. The straight oblique lines represent constant flow resistance, while the hyperbolic curves refer to points of constant input mechanical power. Open and filled symbols refer to soft and hard reed, respectively.

Vibrato tones

Generally, the vibrato rates ranged between 4.5 and 6.5 Hz. This is slightly lower than the values found for vocal vibrato, where it is reported to occur between 5-7.3 Hz, with an average of about 6 Hz in classical lyric singing (Seashore, 1938; Prame, 1994). However, our values are in good agreement with those reported for the flute (Gärtner, 1973). No available data was found about subglottal pressures during vibrato production.

The vibrato parameters ΔP_{mouth}, vibrato extent, and amplitude modulation were measured for *mf* and *ff* tones (Figure 5). In general, these values showed a positive correlation with the dynamic level. Also, hard reeds were blown with higher ΔP_{mouth}.

The following observations applied to all test tones and both reeds. The values for ΔP_{mouth} were greatest in the oboe and smallest in the saxophone and greater at *ff* than at *mf*, also in terms of percentage. For the *mf* tones, ΔP_{mouth} was approximately 10.9, 9.7 and 5.5 cm H$_2$O, or 17%, 21% and 13% of P$_{mouth}$, in the oboe, basson and saxophone, respectively. As for the *ff* tones, the corresponding values were 23.9 (37% P$_{mouth}$), 12.4 (25%) and 12.3 (19%) cm H$_2$O.

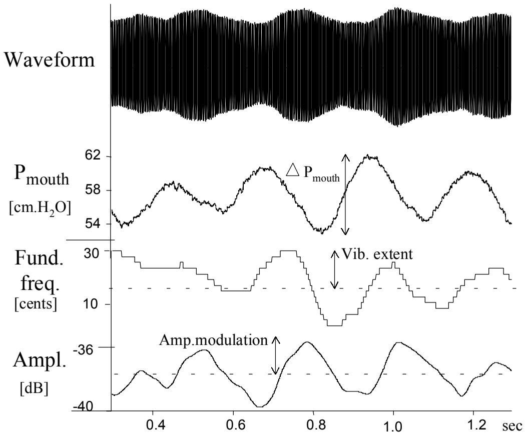

Figure 5. Typical example of vibrato tone waveform taken from pitch A_4 played mf on the bassoon and the corresponding variations of P_{mouth}, fundamental frequency and amplitude. The arrows indicate the parameters ΔP_{mouth}, vibrato extent and amplitude modulation.

The vibrato extent, i.e., the variation in fundamental frequency around the mean, was on average less than ±15 cents at *mf* in all three instruments and for *ff*, maximum values observed were ±17, ±19 and ±42 cents, in the oboe, bassoon and saxophone, respectively. In some fragments, extent of less than ±5 cents were observed in all instruments. These are considerably lower than what is typically observed both in professional classical singing, or about ±70 cents, and in violins about half that amount (Prame, 1997, and personal communication).

The amplitude modulation usually amounted to less than ±1.0 dB in *mf* and more than ±1.3 dB in the *ff*. Greater values were observed particularly for the saxophone where it reached ±2.9 dB in some cases.

Discussion

Accuracy of the method

The method of indirect spirometry, used in this study, contains at least two main sources of errors. The first is the air volume measurement by the pneumotacograph. This has been reported to yield errors of less than ±5% (Yeh et al., 1982). The second is the procedure to have the player inhale through the mouthpiece, aiming to return to the previous initiation lung volume. We estimated this error to less than ±6% from the training task.

In addition, some error could derive from the procedure to maintain constant blowing pressure, embouchure, and dynamic level. Since the subjects were provided with visual feedback of blowing pressure, the deviations in this parameter were minimal, less than 1.0 cm H_2O, generally less than 3% P_{mouth}, and the valid takes were all systematic in terms of dynamical level. Thus, the overall error in airflow estimations should be lower than ±15%. In a previous study, we measured airflow by respiratory inductive plethysmography and found a comparable degree of accuracy, at least for constant flow at P_{mouth} below 50 cm H_2O (Fuks & Sundberg, 1998). As for the resistance and mechanical power, error should not exceed ±19% in the present method.

The SPL measurements in the reverberation chamber were taken after the sound had stabilised, and should have a tolerance of ±1 dB. This corresponds to an error of less than ±26% in the estimated sound power. Consequently, the maximum error in the estimate of efficiency can be expected to amount to approximately ±50%.

An alternative method for airflow measurement is hot wire anemometry (Idogawa et al., 1993; Gilbert, 1991). An advantage of this method is that it could in principle allow direct measurement of particle velocity at selected points inside the bore of an instrument. After appropriate calibration the signal obtained may be decomposed into an acoustical "AC" flow and a "DC" flow, the latter reflecting the airflow across the reed. However, it suffers from the disadvantage of requiring different calibrations for different fundamental frequencies and of non-linearities in the output, particularly for louder sounds.

The indirect spirometry method used here is limited to long sustained tones. However, it seemed to be appropriate for our purposes, being independent of fundamental frequency and blowing pressure, and also non-invasive.

Performance

The length of a musical phrase is ideally determined by the composer. However, the limits set by the player's maximal lung volume and the airflow required by the instrument are also highly significant. For example, a vital capacity of 5000 ml would be sufficient for extending a *ff* tone at the pitch of E_5 of 75s duration on an oboe, while the corresponding values for G_5 played on a saxophone would be about 10s. For a C_4 played *ff* on a bassoon, the duration of playing would be 30s, approximately. In reality the duration will be shorter since players prefer not to use their entire vital capacity. Also important are the limitations imposed by the respiratory control system in terms of the "air hunger" sensations elicited by the restrictions on gas exchange occurring in wind instrument performance (Flume et al., 1995, 1996). The data obtained in the present investigation were recorded under standardised conditions. They indicate that the airflow needed for a musical phrase can be varied within wider limits by changing dynamic level and sound quality. Probably also attacks and tongue articulations can affect the instrument's demand for airflow.

The pressure-flow data observed for the instruments seem to deviate from those reported by Worman (1971) and discussed by Benade (1976). These values refer to a non-oscillating aerodynamical system analogue to the clarinet. According to Worman's pressure-flow curves, airflow decreases with rising pressure under conditions of constant embouchure; by analogy, sound level should also decrease in the clarinet. Our data showed that the players increased both pressure and airflow with dynamic level. The discrepancy apparently indicates that the players do not play with a constant embouchure, but rather change it from tight to loose, when they increase loudness. Interestingly, Worman's curve has been implemented in breath-controlled synthesisers (Rovan et al., 1997). Wjinands & Hirschberg (1995) have complemented Worman's study, showing that the pressure-flow curve of a double reed is considerably different from that of a single reed and contains discontinuities.

The two reeds used in each instrument were considered as very contrasting in terms of hardness of playing, i.e. they clearly differed with respect to the input pressures required for playing at similar levels including the threshold (*pp*). However, essential differences may also exist between reeds rated to have the same hardness (Fuks, 1995).

Vibrato

Gärtner (1973) studied 12 professional flutists while performing vibrato tasks, using acoustical, electromyographical and x-ray imaging. He found that there were players who had a predominant thoraco-abdominal while others had a predominant laryngeal activity for producing the effect. Previous studies on vibrato in professional woodwind players reported movements in a larynx with a narrow glottis. It was concluded that a flow modulation was generated by the glottal oscillations, which caused the vibrato (Weait & Shea, 1977; Mukai, 1989). This probably refers to what is generally called "throat" vibrato. On the other hand, the wide pressure oscillations observed in our players, reaching more than 20 cm H_2O in some cases, can hardly be produced exclusively by changes of flow resistance in the glottis. Van den Berg (1956) found transglottal pressures during phonation typically amounting to 5-20 cm H_2O. However, phonation involves periodic complete glottal closures, which does not normally occur in vibrato tones produced on reed woodwind instruments. Therefore, solely the glottis cannot produce the pressure oscillations observed. Alternatives are represented by the embouchure and/or by the modulation of the expiratory muscle forces, those actually generating the airflow. Embouchure vibrato is commonly used in the saxophone and some mouthpieces are manufactured with an elastic component, which permits slight deformations in the mouthpiece chamber, thus contributing to the vibrato production. Since our subjects were instructed not to produce "lip" vibrato, the hypothesis of the thoraco-abdominal mechanism seems a more plausible origin of the present vibrato examples. The flute vibrato is assumedly a special case, since the blowing pressures are much lower and the airflow much higher than in reed woodwinds (Gärtner, 1973).

Future development and applications

This investigation was confined to specific notes across the normal range of the instruments. Although each of the pitches selected should be representative of neighbouring notes, it would be relevant to complement this study with data covering the full compass of the reed woodwinds. In addition, other wind instruments should be included in future work.

We found clear differences between the soft and the hard reeds. It would be interesting to study in more detail individual reeds during the process of reed making, by systematically changing their thickness and other dimensions. A somewhat similar approach has been applied to the study of the acoustics and construction techniques of the violin (Jansson & Niewczyk, 1989). The detailed information on the reed behaviour and on the impact of these subtle modifications should be of importance for performance and for reed design and manufacturing.

The airflow data, together with the pitch and dynamical level information, may be implemented in a program for predicting breath requirements of a given score, for instance represented in the midi format. This would be useful in teaching woodwind instruments. Also it may serve as a useful tool for composers, by providing estimates of respiratory demands of a piece/phrase.

In the field of electronic instrument technology, our findings should be useful in developing realistic artificial mouthpieces and input systems, so as to optimise the multidimensional possibilities of wind control and the outcome of the players' well-established performance skills (Bowsher, 1988).

Also, an algorithm of automatic performance might include the input parameters data and other appropriate settings in order to simulate the respiratory patterns of a player, thus generating a more realistic interpretation. This algorithm might be translated into a set of automatic interpretation rules (Friberg, 1995).

Conclusion

This study complements already available data on input parameters in realistically played reed woodwinds by considering tones that cover the typical range of the instruments and by comparing two contrasting reeds, a hard and a soft. Differences between extreme types of reeds were found, indicating how such reeds behave in terms of sounding properties and mechanics. Also, the data produced by those dissimilar reeds would establish a range in which most of reeds should usually operate.

The airflow was found to systematically increase with blowing pressure and dynamical level in all instruments. This complements predictions made in previous studies by indicating that players generally change the embouchure from tight to loose when they increase the dynamical level.

Intense vibrato in reed woodwinds was found to require comparatively wide pressure undulations, which cannot be produced merely by the laryngeal mechanism described in previous studies. Mainly, expiratory muscle forces would produce them.

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Appendix

Table 2. Instruments, mouthpieces and reeds used in the experiment

Instrument	**Brand, model and serial number**	**Mouthpiece/ bocal**	**Reed brand and characteristics**
Oboe	Marigaux, France, Automatic, s.n. 10499	n.a.	soft reed (“American” scraping), hard reed (“German” scraping) handmade
Clarinet	Buffet-Crampone, France, Festival, s.n. 303384	Vandoren B40 mouthpiece	Rico 1.5, soft and Vandoren 4.0, hard reeds
Alto Sax	Conn, USA, 20M,s.n. N252008	mouthpiece Selmer S 80 D	Vandoren 2.5/4.0 reeds
Bassoon	Heckel, Germany, 4744	CD1 Heckel bocal	a soft and a hard reed, handmade

Table 3. Experimental data for Oboe, including raw and calculated values.

tone (reed type)	dynamic level	SPL[dBA] room	SPL rev. chamber	pmouth [cm H2O]	meanflow [ml/s]	resistance [cmH$_2$O.s/ml]	mech.power [W]	soundpower [mW]	efficiency [%]
C4 (soft)	pp	74	86	38	54	0.69	0.20	0.20	0.10
"	mf	78	90	36	68	0.53	0.24	0.49	0.20
"	ff	84	95	49	84	0.58	0.40	1.56	0.39
C4 (hard)	pp	77	91	56	78	0.72	0.43	0.62	0.14
"	mf	84	99	58	110	0.52	0.62	3.91	0.63
"	ff	91	102	70	140	0.50	0.96	7.79	0.81
E5 (soft)	pp	78	89	40	42	0.95	0.17	0.39	0.24
"	mf	90	92	50	61	0.82	0.30	0.78	0.26
"	ff	92	96	68	70	0.98	0.47	1.96	0.42
E5 (hard)	pp	83	88	60	69	0.87	0.41	0.31	0.08
"	mf	92	99	76	89	0.85	0.67	3.91	0.59
"	ff	94	105	88	115	0.76	1.00	15.55	1.56
D6 (soft)	pp	78	85	46	63	0.73	0.29	0.16	0.05
"	mf	83	88	58	67	0.86	0.38	0.31	0.08
"	ff	90	95	80	73	1.09	0.57	1.56	0.27
D6 (hard)	pp	78	86	68	77	0.88	0.51	0.20	0.04
"	mf	84	94	84	96	0.88	0.79	1.24	0.16
"	ff	85	98	97	98	0.99	0.94	3.10	0.33

Table 4. Experimental data for Clarinet, including raw and calculated values.

tone (reed type)	dynamic level	SPL[dBA] room	SPL rev. chamber	pmouth [cm H2O]	meanflow [ml/s]	resistance [cmH2O.s/ml]	mech.power [W]	soundpower [mW]	efficiency [%]
D3 (soft)	pp	51	80	12	74	0.16	0.09	0.05	0.056
"	mf	67	98	19	93	0.20	0.17	3.10	1.836
"	ff	78	99	39	158	0.25	0.60	3.91	0.647
D3 (hard)	pp	54	75	32	114	0.28	0.36	0.02	0.004
"	mf	70	87	52	156	0.33	0.80	0.25	0.031
"	ff	83	99	80	248	0.32	1.95	3.91	0.200
Bb3 (soft)	pp	57	81	12	74	0.16	0.09	0.06	0.071
"	mf	70	92	16	89	0.18	0.14	0.78	0.558
"	ff	75	93	30	179	0.17	0.53	0.98	0.187
Bb3 (hard	pp	60	73	34	115	0.30	0.38	0.01	0.003
"	mf	71	85	47	136	0.34	0.63	0.16	0.025
"	ff	82	97	70	286	0.24	1.96	2.46	0.126
F5 (soft)	pp	64	79	10	93	0.11	0.09	0.04	0.043
"	mf	74	89	14	99	0.14	0.14	0.39	0.288
"	ff	80	90	29	143	0.20	0.41	0.49	0.121
F5 (hard)	pp	74	87	35	92	0.38	0.32	0.25	0.078
"	mf	81	89	42	138	0.30	0.57	0.39	0.069
"	ff	92	97	70	338	0.21	2.32	2.46	0.106
E6 (soft)	pp	72	76	9	102	0.09	0.09	0.02	0.022
"	mf	77	86	16	101	0.16	0.16	0.20	0.124
"	ff	80	93	19	136	0.14	0.25	0.98	0.386
E6 (hard)	pp	74	84	34	130	0.26	0.43	0.12	0.029
"	mf	84	92	30	105	0.29	0.31	0.78	0.252
"	ff	89	101	54	208	0.26	1.10	6.19	0.563

Table 5. Experimental data for Alto saxophone, including raw and calculated values.

tone (reed type)	dynamic level	SPL[dBA] room	SPL rev. chamber	pmouth [cm H2O]	meanflow [ml/s]	resistance [cmH2O.s/ml]	mech.power [W]	soundpower [mW]	efficiency [%]
Eb3 (soft)	pp	84	98	22	285	0.08	0.62	3.10	0.504
"	mf	90	106	24	349	0.07	0.82	19.58	2.383
"	ff	93	109	30	574	0.05	1.69	39.07	2.313
Eb3 (hard)	pp	84	100	40	418	0.10	1.64	4.92	0.300
"	mf	89	105	40	830	0.05	3.25	15.55	0.478
"	ff	94	109	40	917	0.04	3.60	39.07	1.086
G4 (soft)	pp	77	98	20	61	0.33	0.12	3.10	2.583
"	mf	88	102	28	104	0.27	0.28	7.79	2.742
"	ff	95	107	48	144	0.33	0.68	24.65	3.645
G4 (hard)	pp	78	97	36	145	0.25	0.51	2.46	0.481
"	mf	88	105	44	247	0.18	1.07	15.55	1.458
"	ff	96	109	60	517	0.12	3.04	39.07	1.284
F5 (soft)	pp	80	92	20	69	0.29	0.14	0.78	0.577
"	mf	95	103	35	85	0.41	0.29	9.81	3.392
"	ff	98	106	54	149	0.36	0.79	19.58	2.489
F5 (hard)	pp	84	87	36	92	0.39	0.33	0.25	0.076
"	mf	94	101	44	139	0.32	0.60	6.19	1.030
"	ff	99	109	70	137	0.51	0.94	39.07	4.166

Table 6. Experimental data for Bassoon, including raw and calculated values.

tone (reed type)	dynamic level	SPL[dBA] room	SPL rev. chamber	pmouth [cm H2O]	meanflow [ml/s]	resistance [cmH2O.s/ml]	mech.power [W]	soundpower [mW]	efficiency [%]
Bb1 (soft)	pp	65	82	21	156	0.13	0.32	0.08	0.024
"	mf	73	88	20	246	0.08	0.48	0.31	0.064
"	ff	77	94	24	438	0.05	1.03	1.24	0.120
Bb1 (hard)	pp	71	87	30	292	0.10	0.86	0.25	0.029
"	mf	76	93	30	350	0.09	1.03	0.98	0.095
"	ff	80	97	46	597	0.08	2.69	2.46	0.092
D3 (soft)	pp	74	82	22	118	0.19	0.25	0.08	0.031
"	mf	84	88	24	144	0.17	0.34	0.31	0.091
"	ff	88	94	40	256	0.16	1.00	1.24	0.123
D3 (hard)	pp	75	93	34	186	0.18	0.62	0.98	0.158
"	mf	82	100	38	246	0.15	0.92	4.92	0.537
"	ff	87	102	60	347	0.17	2.04	7.79	0.382
C4 (soft)	pp	70	82	34	75	0.45	0.25	0.08	0.031
"	mf	79	94	40	126	0.32	0.49	1.24	0.251
"	ff	81	103	68	129	0.53	0.86	9.81	1.143
C4 (hard)	pp	61	87	36	186	0.19	0.66	0.25	0.037
"	mf	79	99	50	171	0.29	0.84	3.91	0.467
"	ff	80	100	74	214	0.35	1.55	4.92	0.317
A4 (soft)	pp	69	83	30	128	0.23	0.38	0.10	0.026
"	mf	79	94	43	126	0.34	0.53	1.24	0.233
"	ff	85	97	63	182	0.35	1.12	2.46	0.220
A4 (hard)	pp	72	89	38	173	0.22	0.64	0.39	0.061
"	mf	78	93	50	184	0.27	0.90	0.98	0.109
"	ff	81	102	74	219	0.34	1.59	7.79	0.491

Prediction of pitch effects from measured CO_2 content variations in wind instrument playing

Leonardo Fuks

Abstract

The effect of carbon dioxide (CO_2) exhaled by wind instrument players on the resulting pitch is investigated. A theoretical-numerical approach is applied to determine the dependence of sound velocity on the percentage of CO_2 contained in the air. Realistic performance data were obtained from experiments in which a professional musician played a clarinet and an oboe, while the CO_2 content of exhaled air was recorded together with the audio signal. By calculating the impact of the variation of CO_2 and O_2 contents on sound velocity, considerable effects on the fundamental frequency of the tones produced are predicted.

Introduction

In most wind instruments the respiratory system provides the aerodynamical energy needed to their control and operation. Those instruments are actuated by the air blown through a reed-mounted mouthpiece (reed-woodwinds), a free mouthpiece (air-reed) or by the vibration of the player's lips (lip-reed instruments). The natural resonance frequencies of the instruments are dependent on the geometry of the air column, the dimensions and design of the mouthpiece and the sound velocity in the gas inside the instrument. The mechanical-acoustical coupling between the actuator and resonator is decisive for the sounds produced. Thus, the fundamental frequency, which determines the pitch perceived, is dependent on the resonance frequencies of the instrument bore as well as of the embouchure and the highly varying blowing pressure (Porter, 1967; Fuks & Sundberg, 1996). The resonance frequencies of the bore are affected by the sound velocity, which, in turn, is a function of the pressure, density, temperature and other properties of the gas.

Carbon dioxide (CO_2) is, together with water, the main effluent from the respiratory metabolism. It is produced during the combustion of carbohydrates in the presence of oxygen (O_2) in the interior of the living cells. It is carried to the lungs alveoli by blood circulation and finally exhaled through the airways.

The respiratory control in man relies mainly on the instantaneous partial pressures of O_2 and CO_2 in the blood. Specialised structures in the central nervous system continuously sense these levels and transmit the information to the brain for ensuring optimal and automatic breathing patterns (Staub, 1991). In this complex respiratory control other variables are also involved such as the input provided by sensory nerves, particularly lung and thoracic stretch receptors. The CO_2 levels play an important role in the so-called air hunger that occurs during respiratory manoeuvres, such as breathholding or reduced expiratory flows typically associated with wind instrument playing. The resulting air hunger imposes physiological limits to the duration of musical phrases (Flume et al., 1995; 1996). In wind instrument playing, the CO_2 contents in the pulmonary air may vary considerably with time, roughly from 2.5% just after a deep breath up to 8.5% after a long period of breathhold, as will be demonstrated in the following sections. The reason why the initial percentage is considerably higher than the atmospheric levels ranging between 0.03% and 0.06% (Zenz, 1988), is due to the fact that the ambient air entering the lungs is immediately mixed with the residual air which is rich in CO_2.

Summarising, fundamental frequency in wind instrument playing depends on the properties of the gas inside the instrument. Also, this gas continuously changes its composition with respect to the content of CO_2 and O_2. These changes should affect the fundamental frequency to some extent. The purpose of the present study was to provide an experimental and theoretical basis for further analysis of this phenomenon by documenting the CO_2 variation during performance of sustained tones and musical phrases in wind instrument blowing.

Sound velocity calculated as function of the content of CO_2

The velocity of sound c in a gas can be calculated as

$$c = \sqrt{\frac{\gamma \, . \, P_0}{\rho_0}} \qquad (1.1)$$

where

γ (Gamma) is the ratio of the specific heat of the gas mixture at constant temperature to that at constant volume;

P_0 and ρ_0 are the pressure and density at equilibrium conditions of the gas, or mixture, respectively (Kinsler, 1962);

The quantities P_0 and ρ_0 are temperature dependent. Ambient dry air typically contains nitrogen (78.1%), oxygen (20.9%), argon (0.9%), carbon dioxide (0.03 to 0.06%) and a number of other gases which usually amount to less then 0.05%. Water vapour is found in ambient air at varying concentrations, depending on environmental conditions. The air exhaled by the lungs is always saturated with water vapour because of the respiratory process and the passage through the airways.

For the calculation of the sound velocity of the gas mixture which takes into account the addition of comparatively low concentrations of CO_2 and water vapour, the following expressions can be used (Nederveen, 1969):

$$\frac{c}{c_0} = 1 + \frac{T}{546} + \sum_v \frac{1}{2} r_v \left[1 - \frac{\rho_v}{\rho} - \frac{2(h_v - h_0)}{h_0(2 + h_0)}\right] \qquad (1.2)$$

$$\frac{\rho}{\rho_0} = 1 - \frac{T}{273} + \sum_v r_v \left(\frac{\rho_v}{\rho_0} - 1\right) \qquad (1.3)$$

where

c = velocity of sound in the gas mixture

c_0 = velocity of sound in typical dry air, at 0ºC

ρ, ρ_0, ρ_v = densities of the mixture, the typical air and the additional gas, respectively

r_v = fractional pressure of additional gas

T = temperature of the mixture, in Centigrade.

h_0, h_v = number of degrees of freedom of standard air and each additional gas, respectively, whereby

$$h = \text{Int}\left[\frac{2}{(\gamma - 1)}\right] ; \qquad (1.4)$$

Int [ ] is the closest integer value of [ ]

Nederveen (1969) used the above mentioned expressions for estimating the effect of temperature on sound velocity of a saturated air mixture containing 2.5% of CO_2 with temperatures ranging from 15ºC to 40ºC. The percentage of exhaled O_2 was assumed to be the same as in ambient air. It is important to note that the amount of water vapour in saturated air increases with temperature. Saturated air at 15ºC has a specific humidity of 10.7 g of water/kg of air and at 40ºC it corresponds to 48.8 g of water/kg of air (ASME, 1967). A quasi-linear variation of approximately 5% was calculated for c between those two temperatures, corresponding to ca 85 cents increase of resonance frequency variation in an air column.

The amount of O_2 in the air, however, is not constant along the respiratory process and a continuous decrease will take place from the initial value of 20.9%. O_2 consumption is dependent on many metabolic processes and is not directly related to the CO_2 production. The oxygen atoms contained in the exhaled CO_2 are supplied by the carbohydrates, while the O_2 enters in the production of water.

The O_2 contents in the alveolar gas may achieve a minimum value of 14% (Schmidt & Thews, 1983). This means that the exhaled O_2 should start with a concentration close to the ambient 20.9% and progressively decrease to a plateau around 14%.

Our first task consisted of calculating the sound velocity of air at a fixed temperature and moistened with saturated vapour, as a function of crescent levels of CO_2. We also made an estimate of the additional effect of the changing in the fractions of O_2.

A spreadsheet software (Excel Microsoft 7.0) was used to accomplish a calculation routine following expressions (1.2) and (1.3) above, the input data being displayed in Table 1 of the Appendix. A temperature of 25.5ºC is assumed as the equilibrium value for a warmed up instrument, in good agreement with previous measurements in the oboe as 25.6ºC (Meyer, 1961) and in the flute, 26.8ºC (Coltman, 1966). For the temperature of 25.5ºC, the specific humidity of saturated air is approximately 2.07% or 20.7 g of water/kg of air (ASME, 1967). The density of saturated water vapour at 0ºC and at atmospheric pressure, used in the formula above, is 0.815 kg/m^3. Figure 1 presents the results of such calculations, indicating a relevant variation in the expected sounding pitch with respect exclusively to the CO_2 contents in the gas mixture, solid line in the Fig. 1. As for the O_2 effect, it was assumed an

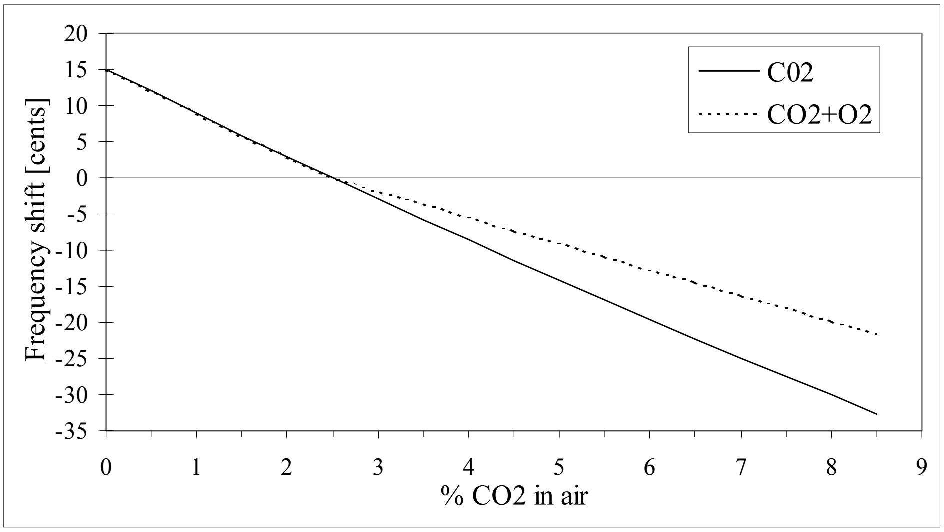

Figure 1. Predicted shift in fundamental frequency in a feedback wind instrument due to variations of CO_2 and O_2 contents. Solid line shows the frequency shift as function of CO_2 percentage for air containing 20.9% O_2. The zero (reference) value for shift corresponds to a CO_2 concentration of 2.5%. The dashed line represents the case in that the O_2 content changes linearly from 20.9% at 2.5% CO_2 to 15% at 8.5% CO_2. Average temperature inside instrument is assumed to be 25.5°C implying a saturation of water vapor (2.07 % specific humidity).

initial level of 20.9% on the beginning of playing (2.5% of CO_2) and a linear decrease (relative to the CO_2 rise) down to 15% at the point of maximum CO_2 percentage, 8.5 %. The resulting curve for the expected effect of CO_2 and estimated effect of O_2 is represented by a dashed line in Figure 1.

Measurements of CO_2 levels during performance

Materials and methods

Two different experiments were done to provide some preliminary data about the CO_2 variations during a musical performance, using the capnographic method (Bhavani-Shankar, 1995). The CO_2 percentage in exhaled air was measured by a Capnograph (CD-3A Carbon Dioxide Analyser and P-61B Sensor Unit). A thin plastic tube inserted in the player's mouth corner transported samples of the air to a pump unit (R-1 Flow Control Device), which, in turn, was connected to the sensor unit of the Capnograph. The analogue output signal from the CO_2 analyser was continuously recorded by a multichannel TEAC (RD-200T) PCM DATA recorder. A microphone (Sony ECM-959DT) picked up the audio signal, which was recorded in a second channel of the same recorder. Experiments were run in a well ventilated room, for which the pre-calibrated analyser showed a reading of 0.03% ambient CO_2.

A professional musician (the author) was the sole subject. During the experiment, the output signals of the Capnograph could not be observed by the player. The experimental protocol was the following:

1. The tones Bb4, G4, Bb3 and A3 (names of actual rather than transposed tones) played on a Bb soprano clarinet. The subject played these tones at a steady *piano* dynamical level, starting immediately after a deep inhalation and sustaining them for as long as possible.
2. A musical piece, Schumann's *Romance No. 2,* op. 94, for oboe and piano played on an oboe. The player first rehearsed the piece as for a recital and then performed three complete recordings, using the same spots for breathing. The *tempo* was 120 quarter notes per minute.

The Schumann piece is considered as particularly challenging for the oboe player because of its very long phrases and frequent wide pitch leaps, entailing high demands both on respiration and intonation.

The instruments used were an automatic Marigaux oboe (s.n. 10499) and a Selmer Bundy

Bb soprano clarinet (s.n. 1211212) with Vandoren´s B45 mouthpiece and 3.5 reed.

Analysis and results from CO_2 measurements

The recorded signals were transferred from the TEAC recorder into computer files, using the Swell™ DSP software package installed in a PC computer with an Ariel DSP-16 board. The results were obtained after a simple procedure of calibration, implying that the zero and range of the computer files were adjusted so as to match the corresponding original readings from the CO_2 analyser.

Clarinet tones

Figures 2.a, 2.b, 2.c and 2.d show the CO_2 build up curves with time for the tones Bb_4, G_4, A_3 and Bb_3, respectively, all played *piano*. After a few seconds all curves show a rather linear increase of CO_2 with time, starting in the vicinity of 3% CO_2 and reaching a maximum of approximately 8% CO_2 after some 50 sec. To estimate the overall rate of CO_2 increase with time during the linear increase phase, trendlines were drawn for each curve by eye. The mean increase during this phase varied between 3.0 and 4.8% CO_2 /minute.

According to the effect predicted before in this article, see Figure 1, the fundamental frequencies of the long notes in Figures 2a-d are expected to continuously shift with time at an approximate rate between -20 to -25 cent per minute, in the linear phase of the curves.

Schumann's Romance for oboe

The three recordings of this piece showed similar and systematic CO_2 curves. Figure 3 shows one of them for bars #1 to #36. In the figure, the score is also displayed. In extreme cases, CO_2 ranged from less than 1.5% to 8.2% CO_2. In general, all phrases started with a steep slope for the CO_2, followed by a progressively smaller increase of this gas with time. The quasi-linear curves that were found for the clarinet were observed also on this instrument in some short segments of the graph, for instance,

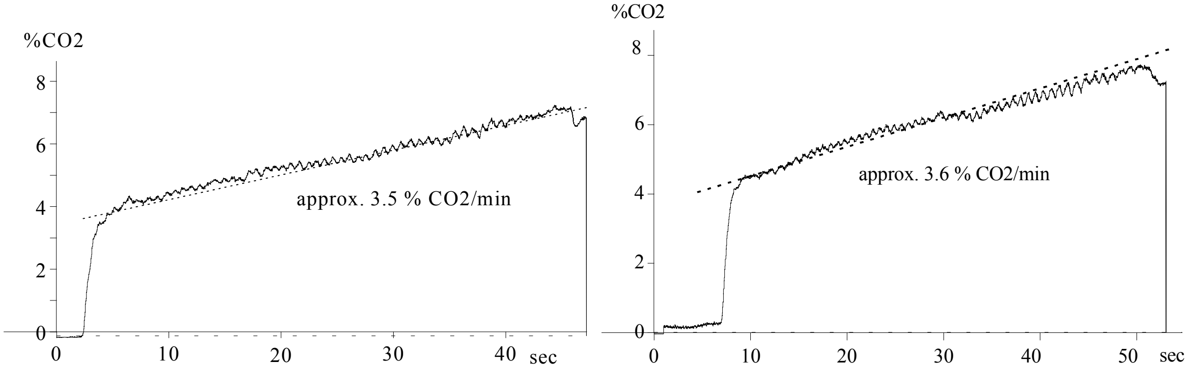

Figure 2a. Note Bb4

Figure 2c. Note G4

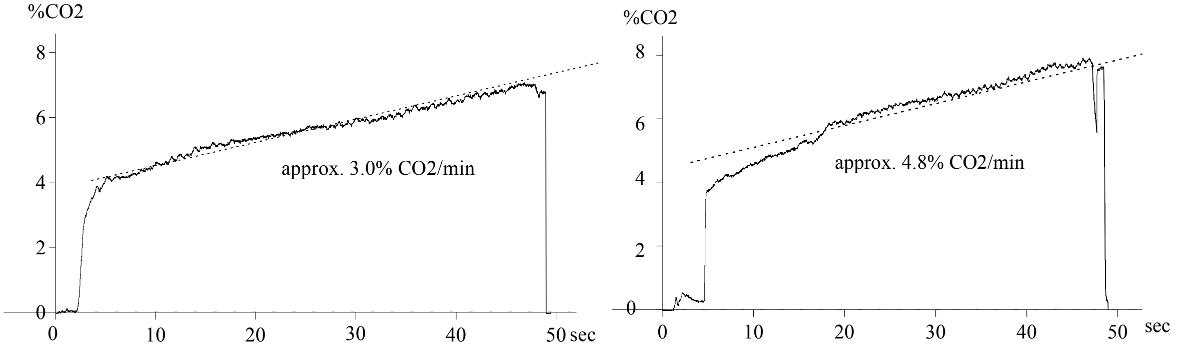

Figure 2b. Note A3

Figure 2d.Note Bb3

Figure 2a-d. CO_2 content against time in exhaled air for the tones Bb4, A3, G4 and Bb3, respectively, played piano *in the clarinet. Reference A4 has a frequency of 440 Hz.*

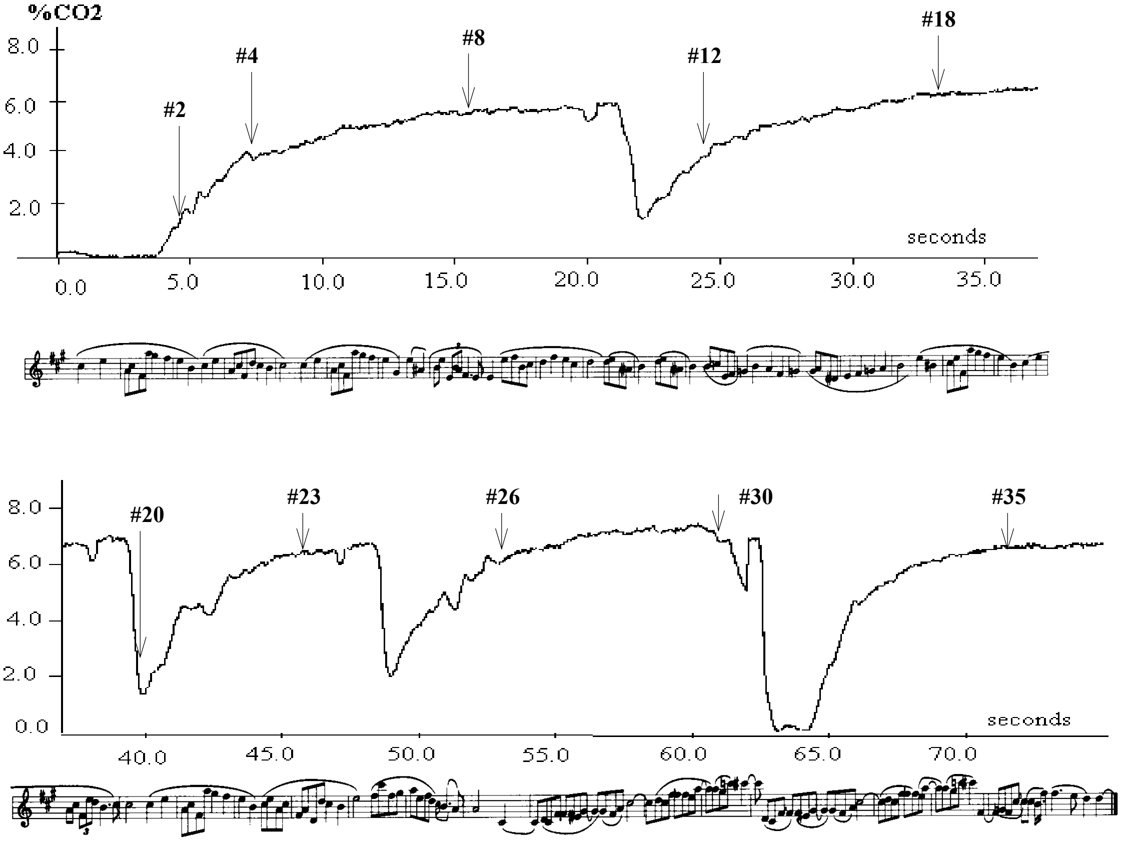

Figure 3. Schumann's Romance 2 for oboe and piano, bars #1 to #36. The curve shows the CO_2 percentages in air entering the instrument with time. The numbers with arrows represent the bar numbers of the music in the score.

the ones corresponding to bars #2-4, #4-8, #12-18 and #26-30. For each new breath a sudden decrease in CO_2 takes place, usually down to a value of approximately 1.5% or 2.0%.

Again referring to Figure 1, the extremes of CO_2 increase observed in Figure 3 would cause a shift in the fundamental frequency of more than -30 cents, other things being equal. Taking into account also a decrease of O_2, a shift of more than -20 cents would still be expected, provided the assumed values for the O_2 content are realistic.

Discussion

Our calculations of the effect of gas changes on sound velocity apply only to the feedback instruments, i.e., the instruments in which the source vibrations are dependent on the resonance frequencies of the air column. Thus, pitch effects of the type considered here should not be expected for non-feedback instruments, such as the human voice and the mouth harmonica.

Temperature is generally regarded as a factor of major relevance to the tuning of feedback wind instruments. Thus, warming the instrument, e.g. by playing or by blowing expired air through the bore, is a routine among wind instrumentalists. As explained in a preceding section, a warming from room temperature of 20°C to 25°C corresponds to a sharpening of the pitch by about +17 cents. It is interesting that the rarely discussed variations of CO_2 content during playing are comparable to the commonly recognised effects of temperature.

The pitch effects of the cyclical variation of CO_2 will depend on the airflow needed to play the instrument. An instrument requiring a great airflow will cause the player to take breaths more frequently than an instrument needing a smaller airflow. As time rather than lung volume is the relevant variable for the CO_2 variation, the pitch effect will be smaller in instruments with a great airflow. Likewise, the player's lung capacity would be a relevant feature as it sets the time limits for producing a given airflow. Thus, players with a relatively small lung capacity, such as children and females, can be expected to encounter a smaller CO_2 variation than male adults.

Presumably, the pitch effects induced by the CO_2 variation are compensated for by the player by means of varying embouchure, blowing pressure and other playing characteristics. This study was confined to the measurement of the variation of CO_2 content in a well ventilated environment and to the prediction of the pitch effects of this variation, assuming a certain variation of the O_2 content. The ambient CO_2 and O_2 contents depend on many factors, e.g., the number of people in a room and the air quality. Obviously, experimental corroboration of our results is needed, particularly with respect to the O_2 variation. Also, direct fundamental frequency analysis during playing artificially excited instruments would be valuable to confirm the theoretically predicted pitch effects.

Some anecdotal evidence and technical recommendations among professional musicians seems to support the assumption that the predicted CO_2 effect on pitch in wind instruments is realistic. Oboe, clarinet and bassoon players tend to agree that there is a general trend for the pitch of the instrument to drop during long phrases. Particularly for the notes in the lower range of the instruments; it may be very difficult to keep the pitch in tune, even with the use of all possible compensatory efforts. It is generally assumed that this is due to a fatiguing of the muscles involved in playing. While this seems a reasonable assumption, there are also reasons to believe that the CO_2 content is also important. For example, the use of a quick inhalation or of the so-called circular breathing technique is said to help restoring the desired pitch. Circular breathing is a technique in which the player keeps blowing into the instrument while air exchanges take place through the nose. To accomplish it, an amount of air is saved in the mouth cavity, isolated from the remaining airways by pressing the soft palate against the back of the tongue. Also, Robinson (1996) quoting instructions from the oboe master Marcel Tabuteau, recommends exhalation of a small volume of air just after the inhalation and before starting a tone on the oboe. This procedure is usually claimed to improve production of soft attacks, facilitate intonation control and create a more relaxed respiratory feeling.

Conclusions

During playing wind instrument such as the oboe and the clarinet, the content of CO_2 in the expired air varies between the ambient level and up to 8.5% in extremely long phrases. This variation alone affects the fundamental frequency of the tones played by more than 30 cent. Although this effect is to some extent reduced by the variation of the O_2 content, the effect of the CO_2 variation on pitch seems a relevant factor in wind instrument playing.

Acknowledgements

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Appendix

Table 1. Properties of some atmospheric gases at 0ºC and at standard pressure of 1 atmosphere (101.325 kN/m²).

Gas	Gamma	h	Density (kg/m^3)	Sound Velocity (m/s)
Air	1.40	5	1. 2929	331.45
Oxygen(O2)	1.40	5	1.42895	317.2
Nitrogen (N2)	1.40	5	1.2505	336.0
Hydrogen (H2)	1.41	5	0.08987	1261.0
Helium (He)	1.66	3	0.1785	971.0
CO_2	1.31	6	1.9768	258.0

Gamma is the ratio of the specific heat of the gas mixture at constant temperature to that at constant volume

h is the number of degrees of freedom of standard air and each additional gas, a function of Gamma (see expression 1.4 in this text)

Respiratory inductive plethysmography measurements on professional reed woodwind instrument players

Leonardo Fuks and Johan Sundberg*

**Rio de Janeiro Federal University- UFRJ- School of Music, Rua do Passeio 98, 20021-290, Brazil*

Abstract

Respiratory movements and lung volume variations during natural performance of wind instrument playing have been scarcely documented in the literature, but may provide a deeper insight into performance techniques, players' physiological characteristics as well as into the physics of the instruments. Using Respiratory Inductive Plethysmography (RIP) respiratory movements of eight professional players (oboe, clarinet, alto-saxophone, bassoon) were measured during playing of exercises and orchestral solo voices. Calibration of the relative contribution of abdominal wall and rib cage regions was achieved from isovolume manoeuvres. Pneumotachometry was applied for absolute calibration of the RIP. Flow through a standard aerodynamic resistance at constant pressure was used for assessing the method of measurement under dynamic conditions. Different possible artifacts are described and discussed. The method yielded linear and accurate results, provided that significant body movement is absent, appeared to be non-disturbing to the musicians, accurate and robust. Depending on instrument and piece the players initiated the breath groups at 55% - 87% and terminated them between 14% - 52% of their vital capacity. Unlike what has been found for singers, the players generally showed simultaneous and in many cases equally important contributions from rib cage and abdominal wall during playing. In extreme cases, inhalations were achieved in approximately 300 ms and reasonably synchronised with the RIP signals.

Introduction

The actions involved in playing reed woodwinds comprise blowing through the instrument's mouthpiece at a varying blowing pressure, airflow and embouchure, resulting in a wide ensemble of sound qualities. For a detailed analysis of musical performance on such instruments, also the player's respiratory activities are relevant.

Data on blowing pressures in wind instrument performance has been documented in a number of studies (Bouhuys, 1964, 1968; Navrátil and Rejsek, 1968; Pawlowsky and Zoltowski, 1985, 1987; Fuks and Sundberg, 1996). Body plethysmography studies in singing and trombone playing have been carried out, although it normally requires the subject to be confined into a closed box with only the head out (Bouhuys, 1968). Cossette (1993) used an ensemble of techniques and devices, including gastroesophagial balloons and magnetometers, to measure internal pressures, muscular activity and thoracic displacements during playing of sustained flute tones. However, to our knowledge, no systematic respiratory measurements have been carried out under realistic performance conditions; airflow has been estimated merely in general terms (Bouhuys, 1968; Pawlowsky and Zoltowski, 1985). An important reason would be the technical difficulties in measuring the passage of air at any point of the system without significantly affecting the instrument and player's behaviour. An investigation specifically on airflow during reed woodwind playing is under preparation (Fuks, forthcoming).

The ventilatory cycle is divided into an inspiratory and an expiratory phase. In the former, the inspiratory muscles of the thorax and abdomen produce a negative pressure inside the lungs, thus causing an inward flow of air through the open airways. During the expiratory phase, which is passive in normal relaxed breathing, the expiratory muscles may act in co-operation with the elastic recoil forces of the thorax and also, to a minor extent, the expansion forces of the compressed air inside the respiratory system. Additional components in the expiratory act is gravity (the body structures' weight) and postural modifications caused by non-respiratory muscles that may considerably change the thoracoabdominal volume. For a more detailed description of ventilation, see references (e.g. Roussos, 1995).

In the present study, ventilatory movements were indirectly assessed by means of respiratory inductive plethysmography (RIP). Two elastic bands are wrapped around the chest and abdomen of the subject; the bands are provided with an electric coil powered by an oscillating unit, see Figure 1. The changes in the cross-sectional areas surrounded by the coils cause changes in the electromagnetic properties of the system. Thus, the individual variations of chest and abdominal volumes produce corresponding variations in the output signal of the RIP. The method is closely related to the two-degrees-of-freedom model for measurement of chest wall volume displacements (Konno and Mead, 1967; Loring and Bruce, 1986). According to this model, the variations in lung volumes are solely reflected in the variations of the two independent compartments, the rib cage and the abdomen, although a good accuracy can be attained only provided that there is no change in body position. The RIP has been widely used for monitoring and measuring respiratory activities in patients, probably due to its relative low-cost, reliability, reasonable accuracy, non-invasiveness and the possibility to separately assess rib cage (RC) and abdominal wall (AW) breathing. The RIP equipment may be used in two different modes: AC and DC coupling. We chose the DC coupling to avoid the drift toward zero output voltage during very long phrases, that may extend over more than 30 seconds in many cases. On the other hand, the use of DC coupling is referred as requiring more attention to calibration, as the system becomes more sensitive to temperature effects (Morel et al., 1983).

In musical performance analysis, the RIP method has been used for studying respiratory activities in classical singers (Thomasson and Sundberg, 1997). In addition, studies have been carried out on the relation between respiration and phonation (Iwarsson and Sundberg, 1996). However, to the authors' knowledge, it has never been applied to analysis of wind instruments performance. The primary objective of this paper was to apply the RIP method to professional wind players and to assess its accuracy and suitability, so as to gain some experience for future investigations. A second objective was to provide representative data from professional musicians performing a given set of tasks. These tasks consisted of playing pieces which raised different respiratory demands on the player, and performing some standardised respiratory manoeuvres without the instrument.

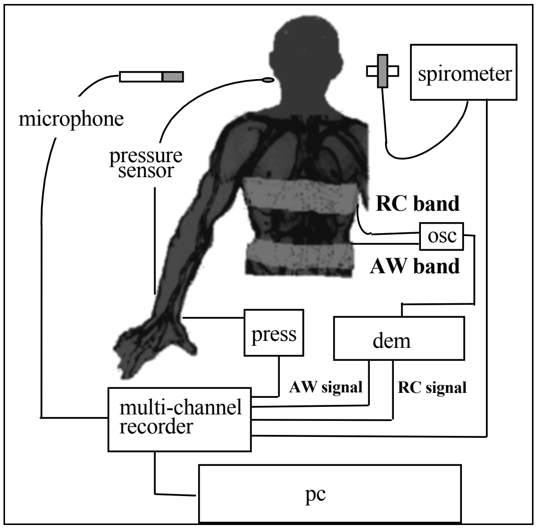


Figure 1. Experimental setup comprising the RIP, auxiliary instruments and recording equipment. The RIP equipment consists of the two elastic bands (RC and AW band) fed by a DC coupled oscillator (OSC), and a demodulator (DEM) comprising also an amplifier. The AW and RC signals are recorded into a multichannel TEAC PCM data recorder. A spirometer was used in inhalatory manoeuvres for calibration of the RIP. The audio signal was captured by a microphone, and mouth pressure by a pressure sensor. For the subsequent analysis, the data were ported to a PC. Illustration adapted from a drawing by L da Vinci.

Calibration is a classical concern in studies using RIP. This applies to the present investigation in particular, as musical subjects often tend to move considerably during playing. Also, they may perform a number of complex movements in the chest region when accomplishing a musical task involving series of sudden shifts in blowing pressure (Fuks and Sundberg, 1998). In the calibration of RIP, several models of the ventilatory system can be applied and many procedures can be used for establishing reference volumes (Strömberg, 1996).

Material and methods

Two professional players of each of the instruments clarinet (in B flat), alto-saxophone, oboe and bassoon, served as subjects in the experiment. All of them had a minimum experience of 15 years and their ages ranged between 31 and 48 years. They received, at least 24 hours prior to the experiment, the scores that they were supposed to play and the instruction to prepare themselves as for a concert. The subjects were only aware of that the experiment was related to measurements of respiratory movements, that it would take approximately one hour, and that they would be paid with the equivalent of one hour of private teaching.

The setup is shown in Figure 1. The bands attached to the subject are connected to a RIP unit, the output of which is recorded on a multichannel TEAC PCM DAT recorder together with audio signal from a microphone placed at 1 meter distance, the pressure signal from a thin pressure transducer (Gaeltec CTO-2 thin film strain gauge catheter, 2mm diameter; Gaeltec S7b amplifier), and the signals from a previously calibrated electrospirometer (Silverman-Lilly type, Mercury CS-5, F100L flowhead), also called a pneumotachometer. This spirometer measures flow in terms of the proportional pressure drop across a resistance provided by a very fine mesh screen. The spirometer was used throughout the experiment to secure parallel and accurate measurements of the air volumes displaced by the players' lungs. It was only used during inhalation. As all subjects were very conscious about respiratory acts, we realised that there was no need for the use of nose clips. During the experiment, all players were in a sitting position, except for the clarinet players who preferred standing. The whole experiment contained three main tasks.

Task 1. A series of respiratory manoeuvres simultaneous use of the RIP equipment with DC coupling and spirometric measurements, without the musical instrument.

a) Calibration and recording of tidal volume during relaxed respiration during 1.0 minute followed by isovolume manoeuvres at the functional reserve capacity, FRC. Figure 2 shows the standard spirometric parameters.

Isovolume manoeuvres (IVM) consist of a series of alternating contractions and expansions of the abdomen and ribcage while holding the breath and keeping the relaxation lung pressure. At FRC, the manometric relaxation pressure is zero, i.e. ambient pressure. If properly performed, this manoeuvre provides an accurate calibration of the contributions of the abdomen and ribcage to lung volume variations (Konno and Mead, 1967; Watson, 1980). The IVM was repeated at least three times, before, during and after the entire experiment. See Figure 2 for an example of data calibration through IVM. The time interval between these procedures did not exceed 15 min.

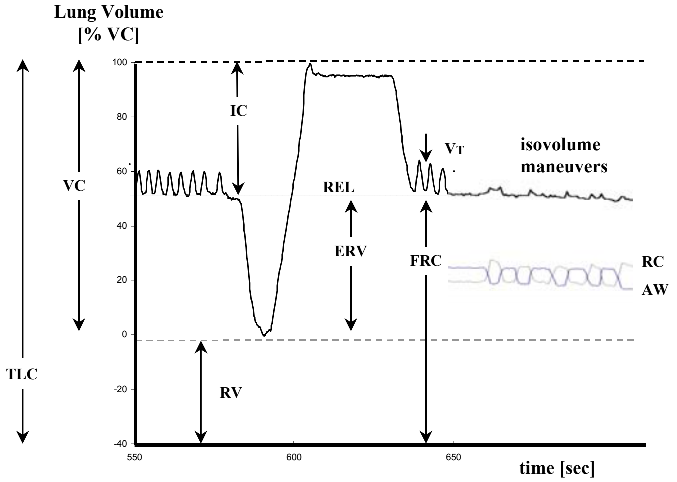


Figure 2. LV data derived by RIP measurement from task 1 illustrating relevant standard spirometric parameters: vital capacity (VC), total lung capacity (TLC), inspiratory capacity (IC), tidal volume (V_t), expiratory reserve volume (ERV), functional reserve capacity (FRC), residual volume (RV) and the respiratory base-line represented by the resting end-expiratory level (REL). The isovolume manoeuvre, performed in the vicinity of ERV was used for weighting the amplitudes of the RC and AW channels such that the sum corresponded to LV.

b) Inhalation up to maximum volume through the spirometer, starting from a relaxed exhalation, i.e. the resting expiratory level (REL) followed by an IVM at that lung volume. This task allows measurement and calibration of the system with respect to the inspiratory capacity (IC), i.e., the difference between total lung capacity (TLC) and FRC.

c) Maximal inhalation through the spirometer preceded by maximal exhalation. This task was used for determining the vital capacity (VC).

d) Production of three different pressures: relaxation pressure, 40 cm H_2O and 70 cm H_2O during breathhold at different lung volumes: FRC, FRC+ 40%IC and FRC+ 80%IC. The value for IC was taken from task 1b. Visual feedback was provided to the subjects by means of the meter of the pressure transducer.

Tasks 1a, 1b, and 1c were recorded twice. The subjects were instructed to produce all respiratory movements while keeping the same posture. In accordance with a standard procedure for spirometric measurement only that take was used in the subsequent analysis that gave the greatest IC and VC, respectively (AARC, 1994).

Task 2. Playing three music examples on the instrument: (a) a scale exercise covering the typical range of the instrument and containing articulatory markings and dynamic signs, shown in the Appendix, score 1; (b) the whole solo part of *Bolero* by M. Ravel, see score 2 in the Appendix, and (c) the obbligato part of "*Jesu bleibet meine Freude*", from J.S. Bach's cantata BWV 147, score 3 in Appendix, at a rather fast tempo (MM between 75 and 100). The players were asked to follow the dynamic instructions in the scores and to play at a level comparable to that required in a concert hall performance. They were also instructed to use conventional breathing, as opposed to circular breathing, a technique that permits simultaneous inhalation and playing. The pieces were recorded until a musically and technically acceptable quality was obtained.

Task 3. Deep inhalation, as if just before playing a long phrase, through the spirometer, followed by continuous blowing at a pressure of 30 cm H_2O across a standard resistance (0.359 cm H_2O.sec/ml) provided by a narrow metal tube. This task took place until the player started to feel breathlessness to a degree that elicited a longing for interrupting the exhalation. Visual feedback of the blowing pressure was provided to the subjects by means of a Bourdon tube manometer connected to the mouth. Thereafter, the player inhaled again through the spirometer mouthpiece and immediately repeated the same task. The quasi-constant flow thus produced was expected to be approximately 83.3 ml/sec (5.01 l/min).

Calibration

Before the recordings the pressure meter was calibrated by immersing the transducer into a graduated water column and adjusting the gain and zero on the amplifier box (Gaeltec S7b). The spirometer was calibrated by means of a standard 3000 ml cylinder, with flow in both directions. Although the results differed less than 4% among directions, the spirometer was used only for inhalation, because of its sensitivity to gas humidity and density. As for the RIP, the gain potentiometers of the DC-coupled amplifiers were set to maximum while the offset was adjusted to accommodate the voltage variations corresponding to the subject's maximum inspiratory and expiratory movements. The calibration of the two RIP channels was carried out after the recording by transferring the data into a spread sheet (MS Excel) and computing the coefficients that gave a constant sum signal for the isovolume manoeuvres; in this way a sum signal was obtained that reflected relative lung volume. Henceforth, the calibrated data from the abdominal wall and rib cage channels will be referred to as AW and RC, respectively.

Analysis

The experimental data stored on the Teac tapes were transferred to a personal computer by means of a DSP board (DT-2821 Data Translation) and recorded as SWELL© files under the SMP format, sampling frequency 5 kHz per channel. Then, the EXTRACT© program (Spruce Applications) was employed to convert and downsample the SMP files into text files allowing transfer to MS-Excel© spread sheets. The final sampling rate was 5 Hz, which was sufficient for most of our analyses. For analysis of the durations of breath pauses, however, the 5 kHz file versions were used, see below.

Task 1a was designed for the calibration of the equipment as well as for training the subjects, particularly with respect to the isovolume manoeuvres. Figure 2 shows typical recordings of tidal breathing and isovolume manoeuvres after appropriate calibration.

Tasks 1b and 1c provided the subjects' respiratory profile in terms of IC and VC, see Table 1. Additional information about the subjects is provided by table 5, in the Appendix.

Task 1d was included to allow estimation of the effect of the blowing pressure on the RIP output.

Results

Assessment of method

The first issue to be considered in accounting for the results is obviously the reliability of the measurements, which was elucidated by the experimental material collected in tasks 1 and 3. Thus, in accounting for the results, the chronological order of tasks during the experiment is irrelevant.

A period of at least 3 hours was allowed for the equipment to warm up and the attachment of the RIP bands was carefully done, letting the subject get used to it during the warming up playing. Usually the apparent ERV, as determined from tidal breathing, did not drift appreciably. In cases where the ERV value suddenly shifted because the player changed body posture, it was sufficient to ask the player to resume the initial posture for returning the value to the initial level. Repeated measures of ERV during tidal breathing in sitting and standing position gave values that varied within 8% of VC, approximately. Immediately after a demanding task, such as 1d, 2c and 3, the respiratory pattern presented an expected increase in frequency and amplitude.

The coefficients used for keeping a constant LV during the isomanoeuvres were determined from all such manoeuvres that the player performed. The coefficients at the beginning and at the end of the recording disagreed less than 12%.

The RIP LV for high LV during extended breathhold at relaxation or higher pressures decreased marginally, about 2% of VC during 40 s of breathhold (Figure 3). As can be seen in the figure, the RC decreased slowly while the AW increased or remained stable under these conditions.

The IC/VC ratio was independently and simultaneously measured by two different methods, with the spirometer and with RIP. Figure 4 shows a typical recording and the results for the different players are listed in Table 1, which also shows the discrepancies in % between the RIP and spirometry data. The RIP gave lower values for all subjects, the largest discrepancy amounting to -8.3 %, mean across subjects -6.3, (SD 1.3%). These values suggest that the RIP data either underestimated IC and/or overestimated ERV; however, the errors in the RIP data are reasonably small and during inhalatory manoeuvres the RIP signal seems approximately linear. Table 1 also shows the expected values for VC and IC according to statistical populational measurements (Morris, 1971; Bates & Christie, 1964).

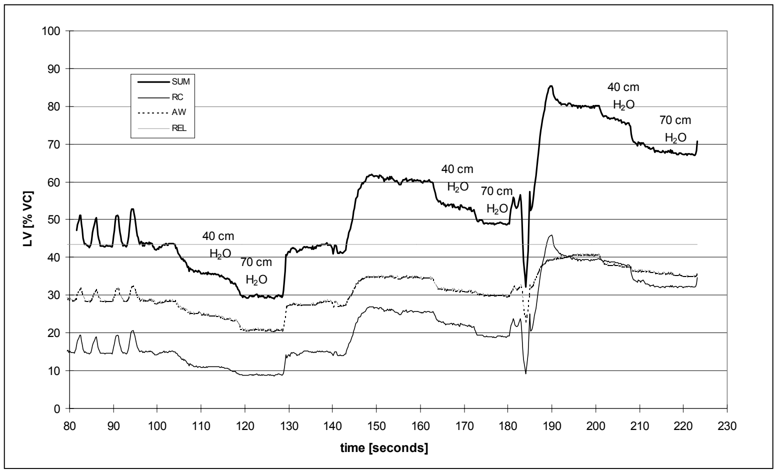


Figure 3. Effects of compression on the RIP LV, AW and RC curves observed during breathholds (task 1d) at 3 different LV and 3 different static lung pressures. The curves show a stepwise descent, as higher static target pressures are produced. After an initial stabilisation period, the RIP LV curve marginally decreased during the breathhold.

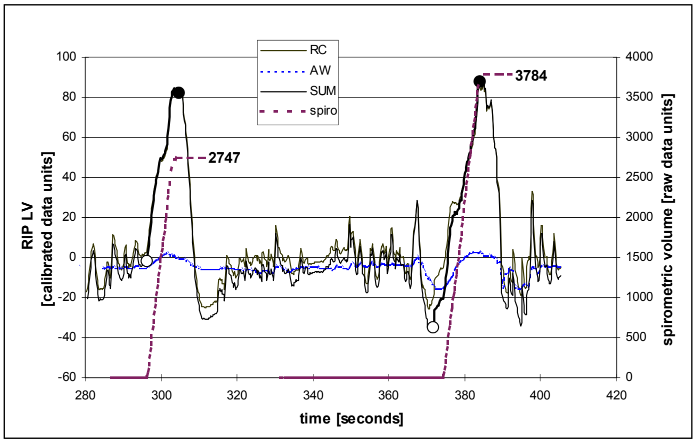
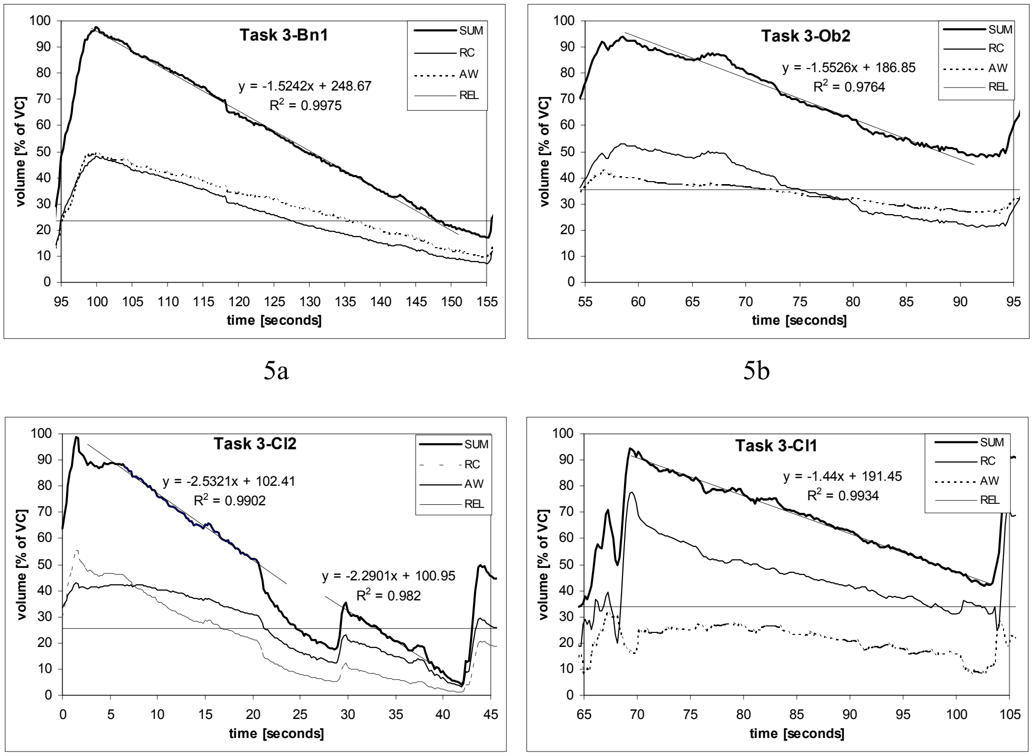


Figure 4. Example of simultaneous spirometric and RIP recordings (heavy broken and solid curves, respectively) obtained from tasks 1b and 1c (IC, left, and VC, right) for volume calibration and determination of the IC/VC ratio. The scales are arbitrary for both the spirometric and the RIP data. The thin dotted and chain dashed curves represent the RIP AW and RC signals. The open and closed circles on the RIP LV curve mark the onset and termination of the inhalation. In the present example, the spirometric IC/VC = 0.72 and the RIP IC/VC = 0.69. More results are presented in Table 1.

Table 1. Lung volume data from the subjects and results from Task 3. Lung volumes measured with the spirometer and RIP techniques. The values in "Normal" rows are the expected values according to populational measurements (Morris, 1971; Bates and Christie, 1964).*

	OBOE		CLARINET		SAXOPHONE		BASSOON	
SPIROMETRIC DATA	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
VC [liters]	5.9	6.0	5.2	2.9	4.8	4.7	5.0	5.5
IC [liters]	4.6	4.2	3.2	2.1	3.7	3.4	3.4	3.5
NORMAL* VC [liters]	5.5	5.5	5.7	4.3	5.0	5.4	5.2	5.8
NORMAL* IC [liters]	3.5	3.4	3.6	2.7	3.2	3.3	3.3	3.7
Spirometric IC/VC ratio	0.78	0.70	0.62	0.72	0.77	0.72	0.68	0.64
RIP IC/VC ratio	0.75	0.66	0.56	0.68	0.73	0.67	0.64	0.59
Discrepancy Spirometer/RIP [%]	-4.3	-6.4	-8.3	-6.5	-5.5	-7.1	-5.3	-7.2
ERV (VC-IC) [% VC]	22	30	38	28	23	28	32	36
FLOW THROUGH RESISTANCE, TASK 3								
slope of LV curves [%VC/s]	-1.32	-1.55	-1.44	-2.53	-1.60	-1.63	-1.52	-1.47
det.coefficient of LV curves, R²	0.997	0.976	0.993	0.990	0.996	0.963	0.998	0.992
estimated airflow [ml/sec]	77.8	93.2	74.9	73.4	76.8	76.4	76.2	81.1
estimated error in flow [%]	-6.6	11.8	-10.1	-11.8	-7.8	-8.3	-8.5	-2.7

The linearity of the RIP data was tested during exhalation in Task 3 at a lung pressure of 30 cm H_2O. Under these conditions, the expected constant airflow would be approximately 83 ml/s, as mentioned. Figures 5a-5d display typical curves obtained from this task. By and large, the LV curve shows a high degree of linearity, indicating both that the player managed to maintain the target pressure quite accurately and that the RIP data were quite linear, at least between almost 100% VC down to REL. Using linear regression, trendlines were computed for the SUM curves, discarding initial and final extremes, where compression and depletion of air seemingly distorted the data. In most cases the second attempt contained less initiation distortion, presumably because the subject was then more acquainted with the target pressure. The linear decrease of the LV curve for Cl2 (Figure 5d), was interrupted when the player changed body posture and then after about 10 s resumed it. Interestingly, the slope of the regression lines for the sections of the curve adjacent to this event was very similar (-2.5 and -2.3) indicating that the RIP data were rather robust, provided that episodes of body movements are discarded.



5a 5b

5c 5d

Figures 5 a-d. Typical RIP curves for the indicated players obtained during task 3 (constant-flow produced at 30 cm H_2O as monitored by the subject on a manometer); heavy solid, light solid and dashed curves represent SUM, RC and AW. The equations for the regression lines and the determination coefficients R^2 are also shown. Detailed results from the eight subjects are presented in Table 1.

The slopes and correlation coefficients for the regression lines are listed for all subjects in Table 1 together with the airflow values derived from the RIP data. The latter were mostly below the expected value, the range of variation amounting to ± 10 ml/s, or 12% of the expected value of 83 ml/s, mean across subjects 79 ml/s, SD 6.3 ml/s. The determination coefficient (R^2) was very high for all subjects, mean across subjects 0.988, SD 0.012 . The Table also shows the air consumption expressed in %VC/s, mean across subjects 1.63 %VC/s, SD 0.38 %VC/s. This consumption obviously varies between players because of different VC. In summary, all these results indicate that the RIP data were acceptable with regard to accuracy and reliability.

In Figures 5 it can also be noted that three of the players decreased the cross sectional area of both the RC and the AW simultaneously. For Cl1, however, the AW remained more constant or even produced a paradoxical manoeuvre, while the LV curve still kept a linear decrease.

Above, the condition of constant lung pressure has been considered. In playing, however, this pressure is varied considerably depending on pitch and loudness (Fuks and Sundberg, 1996). Variation of lung pressure results from compression of the respiratory apparatus and associated effects. Such compression will appear as a decrease of the RIP LV signal, even if the quantity of air is constant and airflow is zero. The magnitude of this effect was assessed using the data from task 1d. Figure 3 presents typical examples, illustrating the effect of intrapulmonary pressure increases on RIP LV during breathhold in sitting position. The pressures were 70 and 40 cm H_2O and relaxation pressure, each produced at lung volumes of 80% and 40% of the IC and at FRC. As expected, the increases of lung pressure are reflected as decreases of the RIP LV signal. There was no significant difference between sitting and standing positions.

These RIP LV decreases can be compared to those that can be computed according to the combined equations for ideal gases relating absolute pressure (*p*), volume (*V*) and absolute temperature (*T*) for a constant amount of gas, at any two different states *0* and *1*:

$$\frac{p_1 V_1}{T_1} = \frac{p_0 V_0}{T_0} \qquad \text{(Eq. 1)}$$

Our experiments took place in a room which temperature ranged between 22°C and 24°C and relative humidity between 35% and 45%. All air volume measurements with the spirometer, therefore, will be considered as with the references of 23°C and 40% relative humidity. During inhalation air is rapidly humidified and warmed on its way to the lungs. Assuming a temperature rise from ambient to body values (23-35 °C), the expansion due to warming would amount to 4.7% of the IC. The effect of the increase in humidity would marginally add to the effect of temperature rise. These effects do not apply to the RIP data, as these data are relative rather than absolute.

The effects of pressure generation on the RIP LV are far more important and not self-compensatory with parallel RIP and spirometric measurements, see Table 2 for an example, as pointed out by Bouhuys (1968). For the relaxation pressures, which typically amount to between 30 and 40 cm H_2O (Agostoni and Mead, 1964) at 100% of VC, the discrepancies between expected (from Eq. 1) and measured RIP LV decrease were approximately 1% and -3% in sitting and standing positions. At higher pressures, however, the discrepancy was greater, up to -14.8%. The lung volumes to be considered must necessarily include the residual volume (RV), as the term *V* in Eq. 1 must represent the whole volume of air in the respiratory system. The compression effect was taken into consideration by measuring ILV at the turning point of the LV curve after inhalation. This implies that the compression of the gas alone does not explain the total decrease of the RIP LV. Another candidate would be the escaping of blood from the thoracoabdominal region, i.e. reduction in the blood return to the trunk, that is often associated with Valsalva manoeuvre (Sharpey-Schafer, 1965; McCool, 1995). Yet another possible source of distortion is change in shape of the chest wall caused by the pressure increase. Table 2 shows a numerical example of RIP LV reduction during task 1d, such as in Figure 3. The same subject performed the compressive manoeuvres at standing and sitting positions. The discrepancies in volume between values calculated according to the gas equations and measured values are presented.

An additional factor that might produce volume variation without airflow is the continuously ongoing change in the composition of air inside the lungs. It has been shown that the change in CO_2 and O_2 contents during long phrases produce an increase in density of less than 1.5% (Fuks, 1997). Therefore, this effect would maximally cause volume decreases of 1.5% of the lung volume, RV included, for very long phrases. As TLC is usually less than 140% VC, the maximal expected contraction due to changes in gas will be 2.1 %

Table 2. Compression effect as observed in one subject, task 1d, while standing (above) and sitting (below). RIP volumes and expected values are displayed as a function of initial inhaled LV (column on the left) and intrapulmonary pressures (relaxation, 40 cm H_2O and 70 cm H_2O). Volume discrepancy between RIP measurements and expected values calculated according to the gas equations (Eq. 1) expressed in % of VC.

standing	LV	equivalent in	relaxation	RIP volume (%VC)			expected volume (%VC)			discrepancy RIP-expected (% VC)		
	%VC	%IC	press. [cm H2O]	relaxation	40 cmH2O	70 cmH2O	relaxation	40 cmH2O	70 cmH2O	relaxation	40 cmH2O	70 cmH2O
	100	100.0	34	95	90	82	95.4	94.6	90.5	-0.4	-4.6	-8.5
	87	72.9	24	85	78	69	84.0	82.1	78.4	1.0	-4.1	-9.4
	71	39.6	16	69	61	52	69.3	66.7	63.5	-0.3	-5.7	-11.5
	52	0.0	0	52	42	31	52.0	48.5	45.8	0.0	-6.5	-14.8

sitting	LV	equivalent in	relaxation	RIP volume (%VC)			expected volume (%VC)			discrepancy RIP-expected (% VC)		
	%VC	%IC	press. [cm H2O]	relaxation	40 cmH2O	70 cmH2O	relaxation	40 cmH2O	70 cmH2O	relaxation	40 cmH2O	70 cmH2O
	100	100.0	34	94	91	86	95.4	94.6	90.5	-1.4	-3.6	-4.5
	88	78.2	24	82	77	70	85.0	83.0	79.3	-3.0	-6.0	-9.3
	65	36.4	16	63	56	52	63.4	61.0	57.9	-0.4	-5.0	-5.9
	45	0.0	0	45	35	30	45.0	41.8	39.3	0.0	-6.8	-9.3

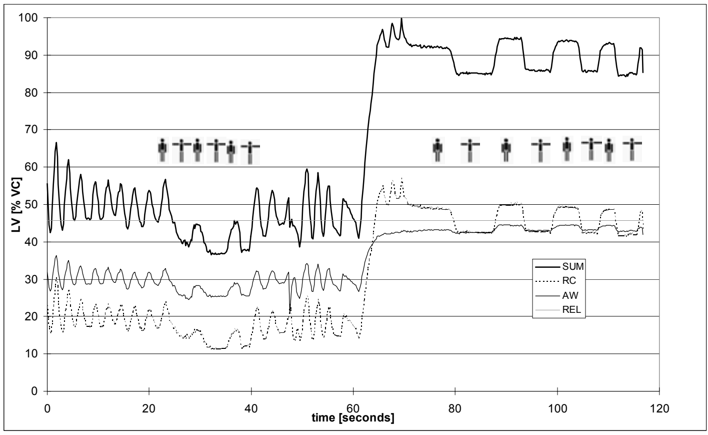


Figure 6. Example of artifact induced on RIP data by a subject who, in standing position and with closed glottis, alternately elevated and lowered his arms as shown by the symbols. The RIP LV signal decreased by 8-9% VC, approximately, both at FRC and at VC.

In addition, some other artifacts also occurred. In some cases the RC and the AW both showed a sudden, parallel increase during playing, presumably reflecting trunk movement (Figure 5c). When the subject (Cl2), while continuously blowing against the resistance, returned to the initial posture, this artifact generally disappeared. Nasal air leakage during playing would lead to overestimation of the airflow through the instrument. Conversely, circular breathing may lead to underestimation of airflow, as the player in such cases inhales through the nostrils while maintaining a blowing pressure confined to the mouth cavity. Arm movements tended to affect the RIP data; when one subject raised the arms from resting position to an angle of 90 degrees relative to the sagital plane, keeping the glottis closed, the RIP LV signal decreased by 8-9% VC, approximately, both at FRC and at VC (Figure 6). At the same time the AW and particularly the RC decreased. Interestingly, this movement would tend to reduce lung pressure.

Music performance data

Figures 7a to 7h show all data points from task 2 for all subjects, performing the standard Exercise, Ravel’s Bolero solo and Bach’s obbligato solo, see scores 1-3 in the Appendix. Each figure is vertically splitted into three parts, one for each musical piece. LV values were represented as percentage of VC, named SUM on the figure. We also provide the estimated contributions of the RC and the AW, both expressed as a percentage of VC. Also shown is the REL as determined from quiet breathing prior to the playing of the examples. In the figures, the absolute values for the three curves are based on the calibration derived from the maximum inhalation/exhalation exercise and from the isovolume manoeuvres. This implies that, at each moment, the SUM values are the sum of the RC and AW values.

The SUM curves generally decreased monotonously throughout the breath phrases and quickly increased between them, thus reflecting inhalation. However, erratic increases and ripple in the SUM curves occur, e.g. in phrase 3 of Ob2 and phrase 3 of Cl2, both during the exercise piece (Figures 7b and 7d). These increases are artifacts probably caused by body movements and/or contractions of non-respiratory muscles. For example, contraction of the *pectoralis major*, *latissimus dorsi* and *anterior serratus* muscles are likely to affect the output from the RC inductive band.

Inhalations comprised apparently synchronous expansions of both RC and AW. These expansions were of comparable magnitudes in all players except Sx1 who expanded his RC considerably more than his AW. Both RC and AW decreased in cross-sectional area during the exhalatory phase. Thus, both RC and AW expanded during inhalation and decreased during exhalation.

Various averages and associated standard deviations derived from the data shown in Figures 7a-h are listed in Table 3. The LVs at the initiation and termination of breath phrases, henceforth ILV and TLV, vary considerably. Depending on players, tasks and instruments the mean ILV ranged from 55% and 87% of VC. The average across tasks was in the vicinity of 60% or 70% of the VC for all instruments. The

TLV also varied between 14% and 52% of the VC. For Ob1 and Ob2 the TLV was clearly above FRC for all tasks, while most of the other players had TLV values that were frequently below the FRC, particularly in the music examples.

OBOE 1

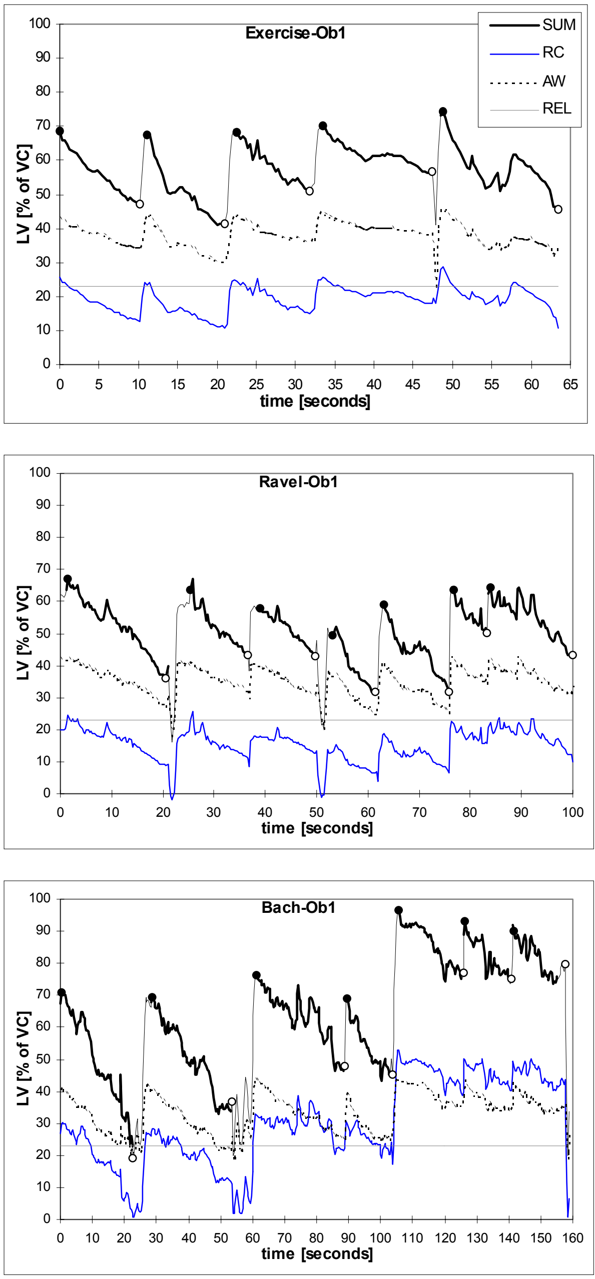


Figure 7a

OBOE 2

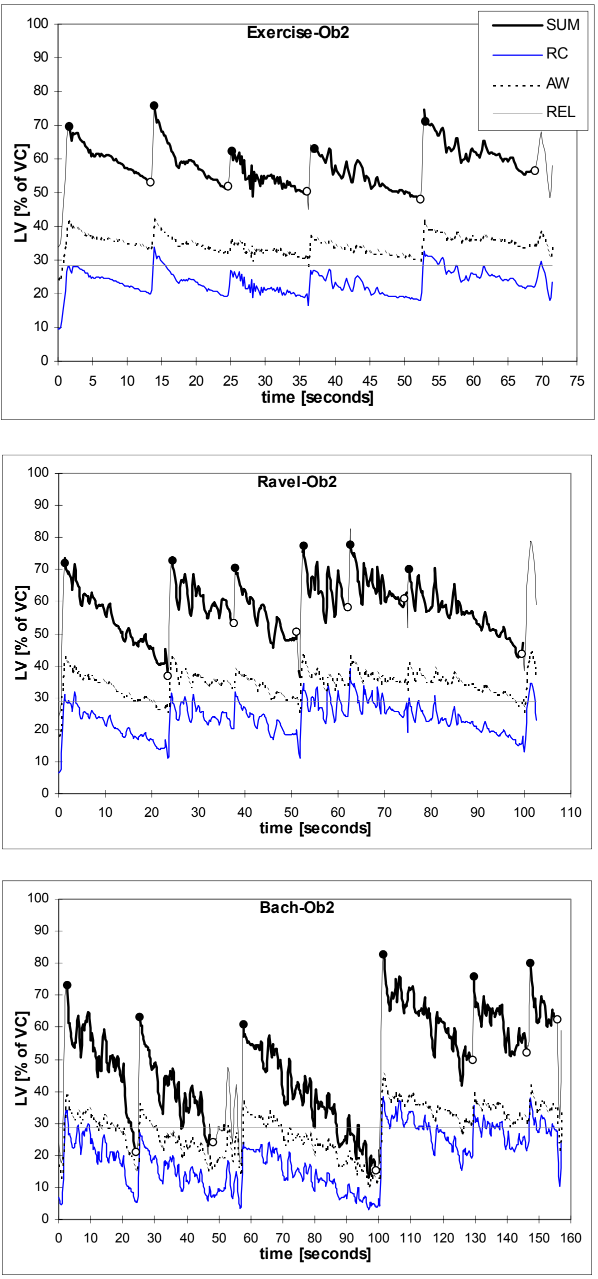


Figure 7b

Figures 7a-7h. RIP LV data in terms of AW and RC and SUM (AW+RC) for all subjects' performance of tasks 2a, 2b and 2c. Each figure is vertically splitted into the graphs pertaining to the standard exercise, Ravel's Bolero solo, and J.S. Bach's piece (Appendix, scores 1, 2, and 3). Filled and open circles represent initiation (ILV) and termination (TLV) of playing, respectively.

CLARINET 1

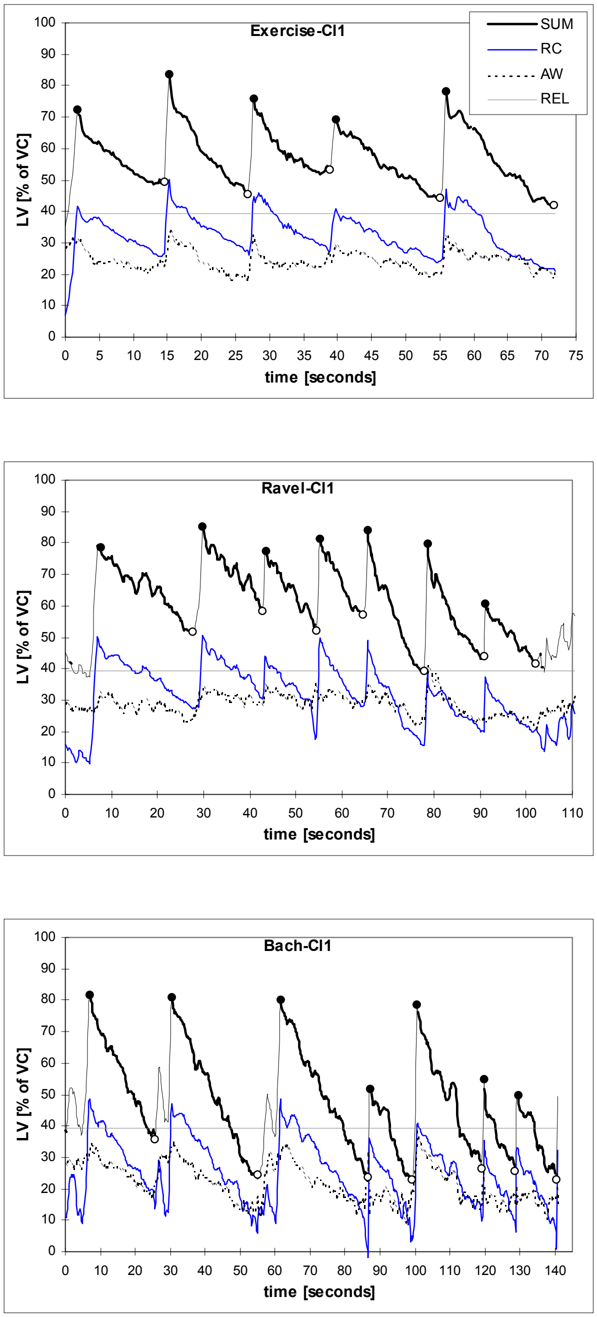


Figure 7c

CLARINET 2

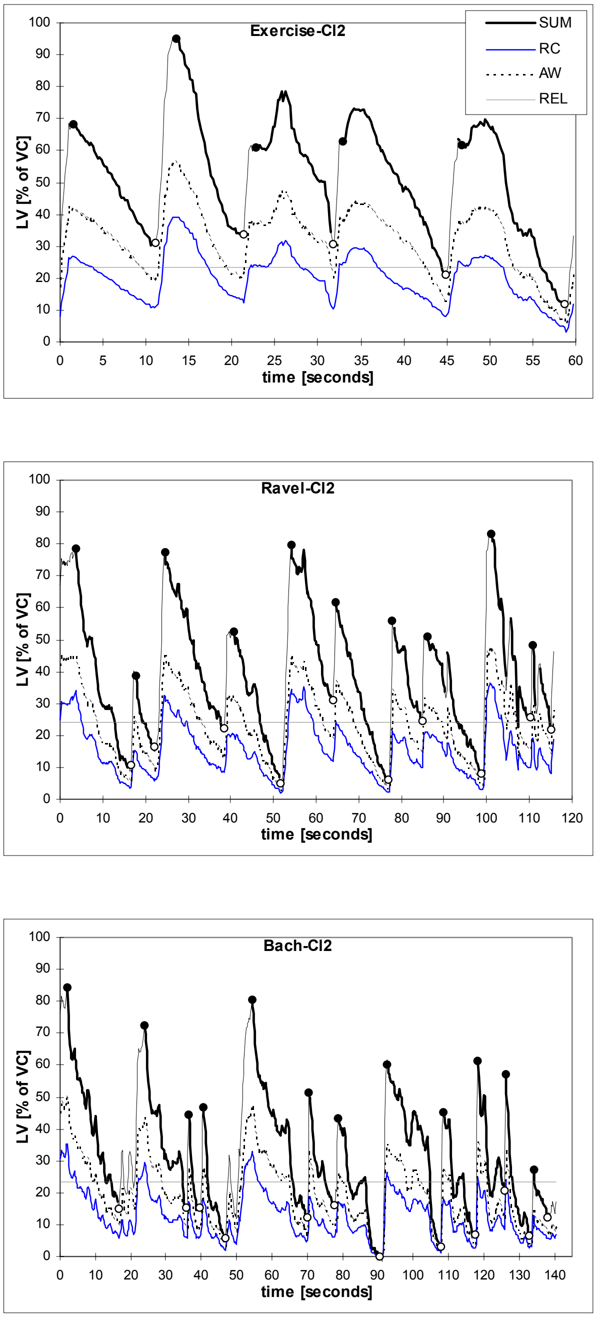


Figure 7d

Figures 7a-7h (continued)

SAXOPHONE 1

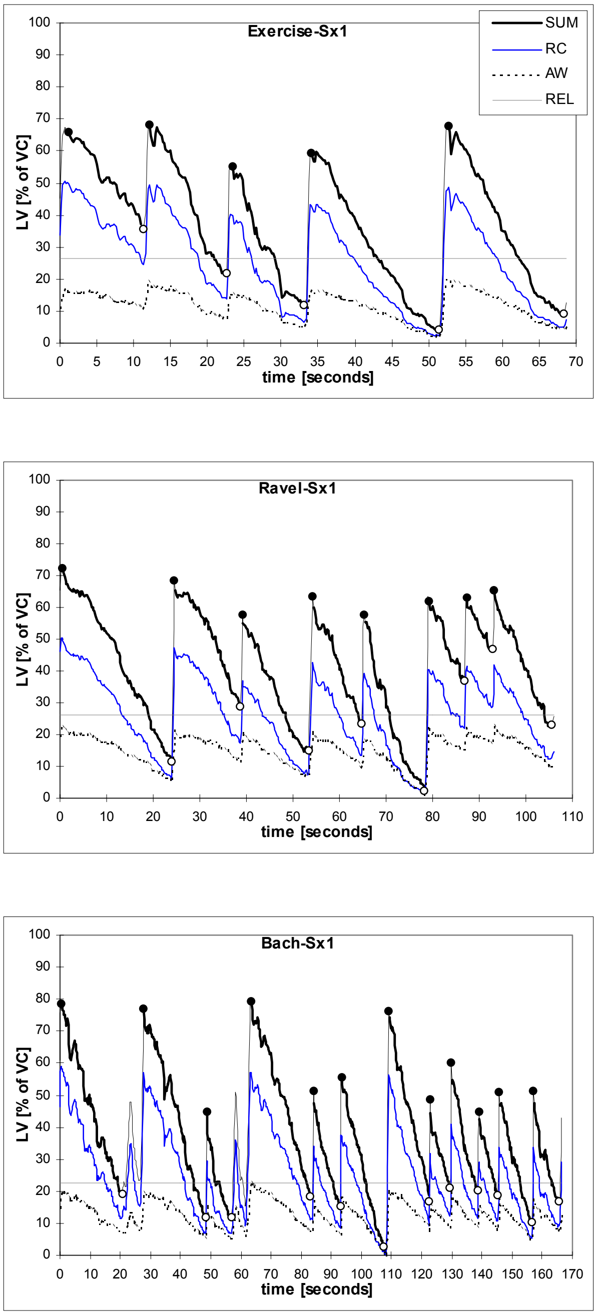


Figure 7e

SAXOPHONE 2

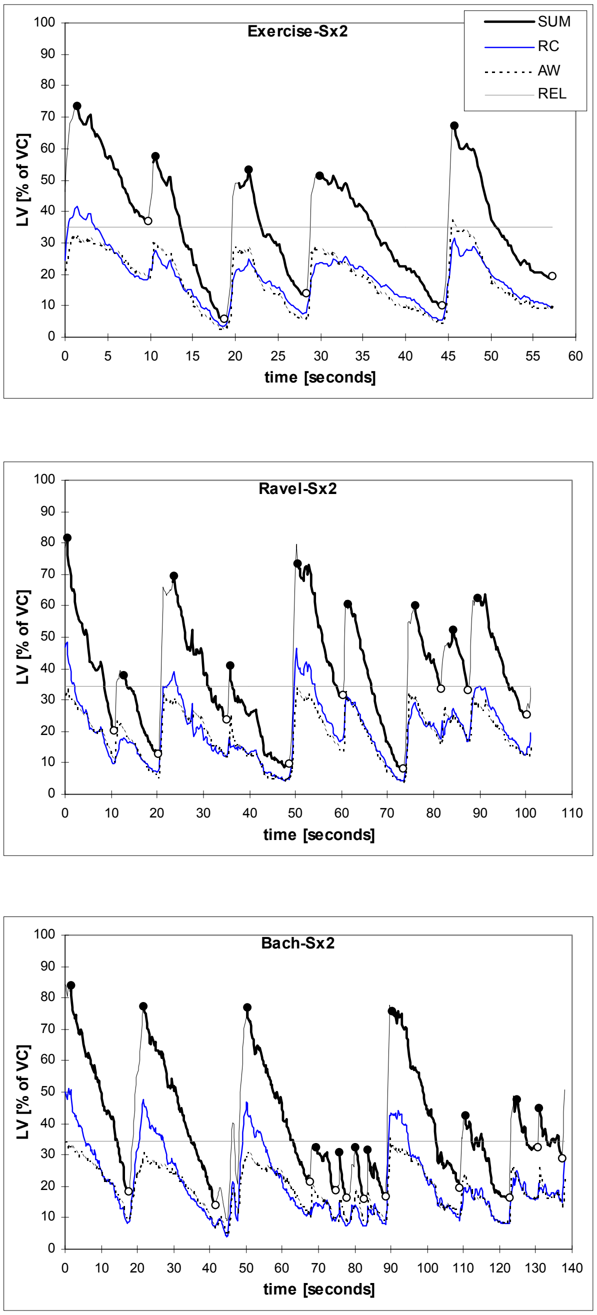
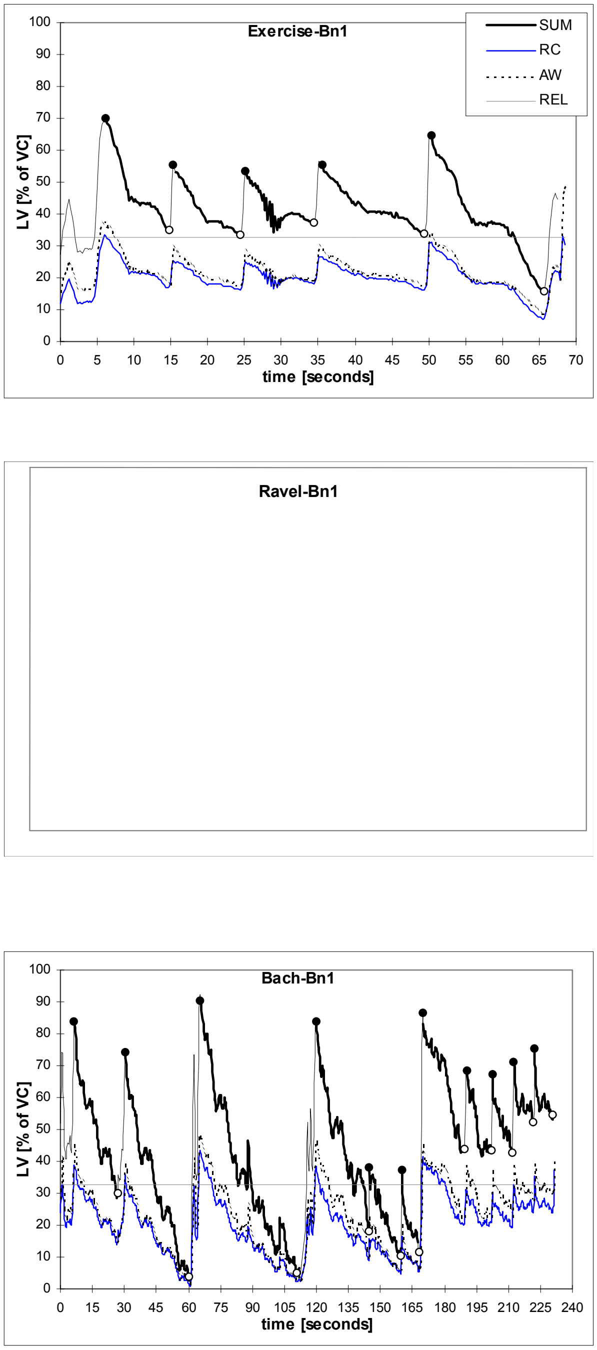


Figure 7f

Figures 7a-7h (continued)

BASSOON 1

BASSOON 2



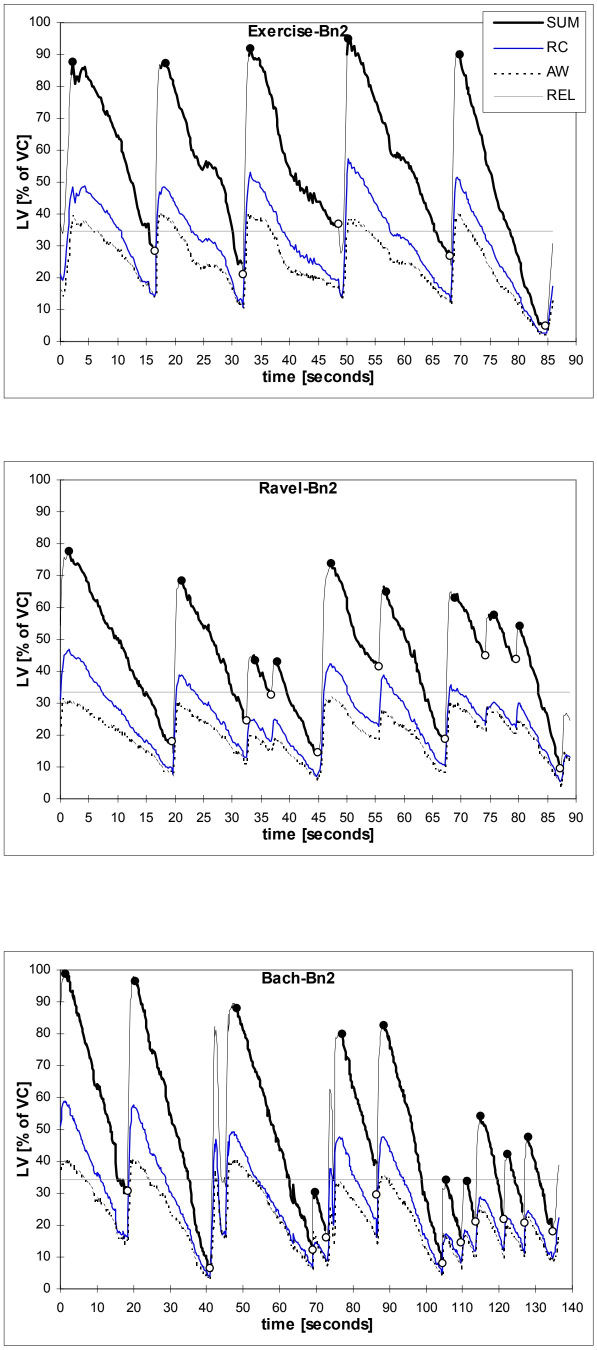


Figure 7g

Figure 7h

Figures 7a-7h (continued). Because of altered RIP-band positions, it was necessary to exclude the data for the Bolero as played by Bn1.

Table 3. Data from performance of the Exercise, Ravel's and Bach's pieces, see scores 1-3 in the Appendix. Average values in bold letters and standard deviations in parentheses. The initiation and termination lung volumes, ILV and TLV are averaged from all phrases and the correlation with the duration of the coming phrase is presented. The mean airflows were obtained by averaging the quotient of estimated air consumption and duration of all phrases in a piece. Data for Ravel's piece with subject Bn1 could not be processed.

		OBOE		CLARINET		SAXOPHONE		BASSOON	
PERFORMANCE DATA		**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
mean ILV (st dev) [%VC]	Exercise	**70** (3)	**69** (6)	**76** (6)	**75** (12)	**64** (6)	**59** (11)	**60** (7)	**87** (4)
	Ravel	**61** (5)	**74** (3)	**78** (8)	**62** (15)	**64** (5)	**61** (15)	///	**61** (12)
	Bach	**81** (12)	**73** (9)	**68** (15)	**50** (18)	**59** (14)	**55** (21)	**74** (15)	**66** (26)
mean TLV (st dev) [%VC]	Exercise	**48** (6)	**52** (3)	**47** (5)	**24** (10)	**17** (12)	**17** (12)	**39** (4)	**24** (12)
	Ravel	**42** (9)	**50** (7)	**49** (7)	**17** (10)	**24** (14)	**22** (10)	///	**28** (14)
	Bach	**51** (26)	**38** (19)	**27** (5)	**14** (8)	**15** (6)	**20** (6)	**30** (20)	**21** (11)
correlation (R) between ILV and next phrase duration	Exercise	0.850	-0.079	-0.413	-0.680	-0.060	-0.180	-0.413	0.920
	Ravel	-0.220	-0.640	0.096	0.496	0.640	0.120	///	0.710
	Bach	-0.460	-0.650	0.916	0.810	0.860	0.900	0.916	0.890
correlation (R) between AW and RC lines	Exercise	0.847	0.955	0.392	0.979	0.960	0.927	0.949	0.987
	Ravel	0.915	0.937	0.590	0.986	0.964	0.935	///	0.969
	Bach	0.787	0.980	0.565	0.989	0.954	0.943	0.988	0.978
mean AW/RC flow (stdev) ratio	Exercise	**0.78** (0.16)	**0.80** (0.14)	**0.50** (0.15)	**1.39** (0.09)	**0.31** (0.04)	**1.17** (0.35)	**1.26** (0.07)	**0.71** (0.06)
	Ravel	**1.26** (0.40)	**0.82** (0.12)	**0.30** (0.30)	**1.49** (0.24)	**0.39** (0.07)	**1.10** (0.60)	///	**0.78** (0.27)
	Bach	**1.05** (0.39)	**0.85** (0.29)	**0.30** (0.31)	**1.45** (0.19)	**0.38** (0.08)	**1.41** (0.95)	**1.29** (0.24)	**0.95** (0.45)
mean airflow (stdev) [%VC/s]	Exercise	**1.9** (0.6)	**1.4** (0.5)	**2.2** (0.6)	**5.6** (1.9)	**3.7** (0.6)	**4.4** (1.2)	**4.4** (1.7)	**4.4** (0.7)
	Ravel	**1.7** (0.5)	**1.6** (0.3)	**2.4** (0.8)	**4.6** (1)	**3.2** (0.5)	**4.4** (1.2)	///	**3.8** (0.9)
	Bach	**1.4** (0.5)	**1.5** (0.5)	**2.6** (0.3)	**5.2** (2.3)	**3.7** (0.5)	**3.2** (1.1)	**2.4** (0.4)	**4.1** (0.5)
estimated mean airflow (stdev) from lung volumes [ml/second]	Exercise	**112** (35)	**84** (30)	**114** (31)	**162** (55)	**177** (28)	**211** (57)	**215** (83)	**242** (38)
	Ravel	**100** (29)	**96** (18)	**125** (41)	**133** (29)	**153** (24)	**211** (57)	///	**209** (49)
	Bach	**82** (29)	**90** (30)	**135** (15)	**150** (66)	**177** (24)	**153** (52)	**117** (19)	**225** (27)

The table also presents the correlation coefficients (R) between ILV and the duration of the coming phrase. In some cases this duration was a clearly significant factor. The correlation coefficient was especially high for the clarinet, saxophone and bassoon players' performance of the Bach example. However, in some cases the correlation was weak or even negative, indicating that other factors were more influential. This is not surprising, as many phrases were far from exhausting the players' VC.

The expiratory airflow obviously varies substantially depending on dynamics, pitch and other musical factors. For example, phrase 2 of the exercise, that was played *forte* (see score in appendix) showed a greater airflow for most players, as can be seen in Figures 5. Yet, the mean airflow across phrases offers a gross estimate that should be of relevance to the breathing behaviour. Such means are listed both in absolute (ml/s) and relative (% of VC/s) units in Table 1. In computing these airflow values, only the ILV and the TLV points were considered. As expected, the oboe showed the lowest values for mean absolute airflow in all tasks followed by clarinet, saxophone and bassoon. The means, however, varied considerably within instruments and in some cases the standard deviations within players were quite high as compared to the means. It should be recalled that no nose clips were used during the recordings. Therefore involuntary nasal leakage cannot be excluded, which might have caused overestimation of airflow. On the other hand, the use of nose clips was deemed too disturbing to the musicians.

The volume displacement ratio AW/RC shows the relation between the estimated contributions to LV displacement from the AW and the RC. Approximations of this ratio were obtained by dividing the differences in the AW and RC signals between the initiation and termination of each phrase. The means and standard deviations of this ratio are listed in Table 1. The mean ratio varies much more between than within players. Dominant RC contributions were observed for Sx1 and Cl1 while for the remaining players the data suggest similar contributions from both compartments or a dominant contribution from the AW, such as in the case of Cl2. This difference between the players may depend on the respiratory strategy acquired during training and possibly also on trunk morphology, muscular development and other factors.

As mentioned the RC and AW curves in Figures 7 showed similar decrease patterns in some players. This similarity was quantified in terms of the correlation coefficient for associated data points of the RC and AW curves for the entire Task 2 examples, including also the inhalations, shown in Table 3. A great similarity in pattern is reflected as a high correlation coefficient, although the curves may differ with respect of a scale factor. Paradoxical breathing movements, i.e., simultaneous increases of AW and decreases of RC or vice-versa would yield low correlation coefficients. High correlation coefficients were observed for all players and pieces, except for Cl1. Thus, changes in cross sectional area of the RC was accompanied by a proportional change of cross sectional area of the AW, and paradoxical breathing movements were not observed.

High correlation coefficients do not necessarily indicate that the AW and RC curves run in parallel. Figures 7 show several examples of such apparently parallel decreases, indicating that the contributions to LV displacement from the RC and the AW were similar. Sx1 on Figure 7e is a clear example of high correlation coefficients for the three pieces not associated with parallel changes in the RC and AW curves, the AW movements apparently contributing much less to the LV displacement than the RC.

Timing of breath pauses

Another aspect of music performance that can be elucidated with the RIP method are the inhalations during breath pauses in continuous playing. Musicians generally locate respiratory pauses in agreement with the musical structure, e.g., during rests notated in the score. In other cases, the breath pauses are carefully inserted at structural boundaries, thus representing a compromise between expressiveness by punctuation and the demand for an ergonomic respiratory program. In still other cases, respiratory pauses are physiologically necessary but musically undesirable. The Bach's piece, played at a fast tempo, was chosen to offer examples of the last mentioned category.

The recordings from all players were examined. The audio files were analysed in the SMP format for identifying and measuring pauses. The files used for this analysis had a sampling rate of 5 kHz; the 5 Hz versions did not allow accurate comparison between the audio, AW and RC signals. Figure 8 shows a typical inhalatory curve for the audio, AW, and RC signals. Every inhalation was marked and the duration of rapid increases of the curves was determined. Then, the RIP data were inspected for the identification of the characteristic inhalatory curves in both RC and AW signals, which in many cases clearly delimited the durations D_{RC} and D_{AW}. Temporal offsets frequently occurred between the beginning of a pause (audio silent) and the initiation of RC and AW increases, OS_{RC} and OS_{AW}, respectively. Table 4 displays the measurements of breath pauses duration D_b and corresponding RC and AW parameters.

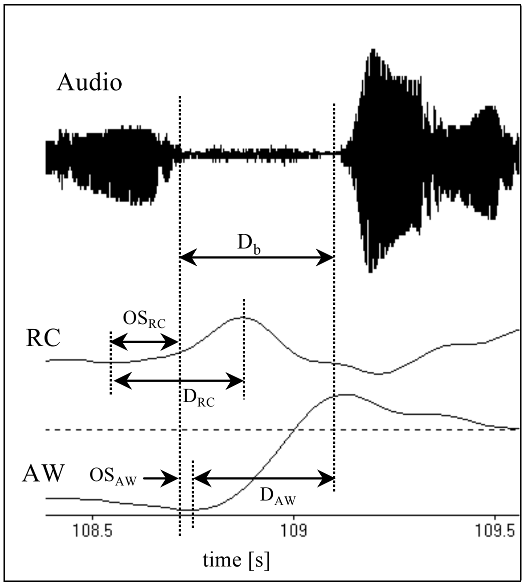


Figure 8. Typical example of rapid inhalation observed during task 2c (Bach). The different graphs show, from top to bottom, the audio signal, RC and AW signals. The breath durations in the audio signal are represented by D_b, while the periods for the increasing in the RC and AW signals are D_{RC} and D_{AW} , respectively. The time offsets between the audio signal and the RIP signals are OS_{RC} and OS_{AW}, a positive value implying that the corresponding RIP signal is increasing ***after*** *the starting of the pause.*

D_b varied between 217 and 448 ms for tempi ranging between 600 and 800 ms beat duration. The AW more often than the RC signal displayed the expected continuous increase during the whole inhalation. This can be seen in Table 4 showing that both the mean and the SD of D_{AW} was closer to those of the D_b than those of the D_{RC}. More importantly, the RC signal showed anomalous characteristics in four subjects: paradoxical movements (subjects Sx2, Bn2) and irregular patterns (Ob1, Bn1) during the inhalation. These values are substantially shorter than those reported for singing (Thomasson and Sundberg, forthcoming). Also, musical context may greatly affect pause duration. Some players, e.g., oboists, often exhale before inhaling, thus exhausting unused air (Rothwell, 1974; Robinson, 1996). This tends to stretch pause duration. In the present

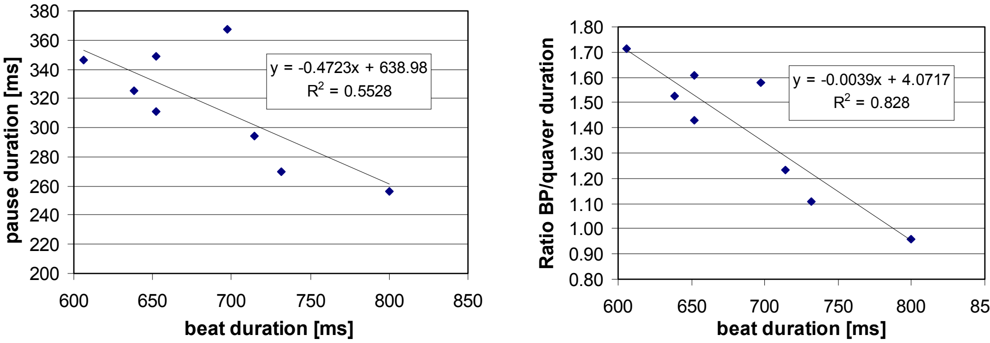
*Table 4. Breath pauses data from Bach's piece performance and related RIP measurements: D_B, D_{RC}, D_{AW}; OS_{RC} and OS_{AW}. See Figure 8 for description of these variables. Star marks * correspond to the different artifices found in the RC data: (*) descending curve during inhalation, (**) irregular pattern, (***) increasing curve in inhalation however starting much before inhalation. The average values for the tempo used by the players is shown in beats per minute (bpm), as well as the nominal duration of each quaver (♫) from the piece.*

	OBOE		CLARINET		SAXOPHONE		BASSOON		ALL PLAYERS			
Breathpauses	1	2	1	2	1	2	1	2	average	stdev	maxima	minima
D_B [ms]	**294** (4)	**367** (33)	**325** (23)	**349** (64)	**270** (35)	**311** (89)	**256** (25)	**346** (45)	312	60	448	217
D_{RC} [ms]	****188** (23)	**427** (6)	**314** (29)	**368** (80)	**233** (27)	* **281** (21)	***	*	298	87	508	162
OS_{RC} [ms]	**6** (24)	**-159** (10)	**-79** (14)	**-56** (51)	**-49** (18)	* **35** (4)	***	*	-51	53	37	-166
D_{AW} [ms]	**365** (80)	**254** (45)	**283** ()	**353** (53)	**298** (48)	**309** (80)	**247** (20)	**305** (41)	309	62	454	222
OS_{AW} [ms]	**7** (92)	**8** (42)	**55** ()	**-104** (18)	**-80** (38)	**-18** (54)	**-66** (11)	**-73** (18)	-55	56	104	-156
tempo [bpm]	84	86	94	92	82	92	75	99	88	7.7	99	75
quaver duration [ms]	238	233	213	217	244	217	267	202	227	//	202	267

case, no exhalations were observed for the short pauses. For these reasons the values listed in Table 4 are probably lower than what could be expected in other musical contexts.

Interestingly, the breath pause duration showed a negative linear correlation with mean beat duration (Figure 9a). On the other hand, the ratio breath pause duration to mean quaver duration showed a strong positive correlation with the tempo (Figure 9b). Thus, the faster the tempo, the longer the breath pauses as measured in terms of the mean quaver duration. This seemingly contradictory finding may be explained by several factors, such as the player's respiratory needs, the air consumption of the instrument, the loudness, the time needed for resuming embouchure, if oral inhalation is used, the expressivity of the pause, and the rhythmic and articulatory demands. The minimum duration of a breath pause in the entire material was 217 ms and the mean quaver duration varied between 202 and 266 ms, Table 4.

It could be hypothesised that when playing music demanding a quasi-constant and quick pace rate, the performer attempts to make the breath quick enough so as to avoid a perturbation of the "motoric" rhythm. In music with a less prominent motoric character, the player is likely to resort to hiding the breath pause in a local tempo variation. In such cases, it would be important for musicians to retain an undisturbed rhythm, as it may play the role of a pacemaker in the listeners by synchronising of their respiratory patterns with the perceived rhythm [Haas, 1986]. To gain more insight into this particular aspect of breathing, a more specific experimental protocol needs to be applied, comprising performance and perception tests.



Figures 9a and 9b. Relationship between breath pause duration, D_b, and mean beat duration for all subjects' performances (a). The correlation is negative, indicating that the faster the tempo, the longer the pauses. Figure 9b shows the relationship between the ratio Db/quaver-duration and mean beat duration, showing a strong negative correlation.

Discussion

Accuracy of the instruments

We used an electronic spirometer for measuring IC and VC. According to Yeh and coworkers (Yeh et al., 1982) such a device, if calibrated with a standard syringe as in the present study, yields an error between 1 and 5%. With respect to RIP, previous studies on the accuracy have indicated an error of less than 10% in normal tidal breathing and error below 20% during large amplitude tidal breathing, under optimal and carefully controlled conditions (Chada et al., 1982). Our RIP estimates of airflow were derived from the constant expiratory airflow experiments. These estimates showed an accuracy similar to that reported in the mentioned papers, although we used a different procedure. Thus, if the conditions above were to be encountered, both our spirometric and RIP data would be reasonably accurate.

Tidal breathing and spirometric data

The establishment of a steady and relaxed breathing pattern before and after each task was very important for obtaining a reliable REL, which was used as a reference throughout the experiment. It has been demonstrated in healthy subjects that voluntary production of FRC does not necessarily lead to accurate results (Salamon, 1974), probably due to the lack of sensorial feedback that may help to observe differences between FRC and other neighbouring volumes. Presumably, this finding also applies to subjects trained in performing respiratory tasks such as wind instrument playing.

Our REL values, which were used for determining the IC/VR ratio, did not closely correspond to the values expected from normative data, Table 1 (Bates and Christie, 1964; Morris, 1971). However, normative values for lung function derived from statistical populational data are unsuitable for predictions as even substantial deviations do not necessarily indicate pathological or abnormal condition (Baur et al., 1996). Deviations of both signs occurred in our subjects, so all of our players did not show a supernormal VC. This is in agreement with previously reported results from careful and extensive measurements on wind musicians, showing no significant respiratory deviations from a similar control group (Schorr-Lesnick et al., 1985). Thus, in spite of the likely benefit of higher pulmonary capacities for wind instrumentalists (Stauffer, 1968), lower than normal values would not *per se* be a disadvantage at professional levels (Stewart, 1987). Also, our subjects inhaled ambient air through the mouthpiece and were asked to avoid body movements during the extreme respiratory manoeuvres. In the standard spirometric method, on the other hand, air is re-breathed within a closed circuit and the subjects are encouraged to exaggerate respiratory manoeuvres so as to produce maximal values (Arborelius, 1996). This procedural difference is likely to affect the outcome. Inhaling ambient air and avoiding great body movements seemed more representative for artistic performance conditions.

REL has been found to differ between seated and standing position, sitting causing a lowering of the REL. VC, however, does not significantly change, implying that the IC increases, when changing from standing to sitting position (D'Angelo and Agostoni, 1995). In some of our subjects, IC increased on the order of 0.5 liters between standing and seated position.

Flexion and extension of the spine can change the chest wall volume on the order of approximately 50% of the VC (Mead et al., 1985). It has been proposed that an optimal deep inhalation would require spine movements to some degree, thus achieving a better fitting of the articulatory joints of the ribcage skeleton (Ward and Macklem, 1995). This suggests that, also in wind instrument playing, spine movements may be advantageous for optimising the mechanical conditions of breathing. On the other hand, such an activity introduces artifacts in the RIP method.

Stability and calibration of the equipment

The calibration of RIP data requires the application of procedures for data collection and of a mathematical model for the computation of the RIP signals (Cohn,1982; Watson, 1980). For data collection, we employed the IVM, and as mathematical model the so-called original linear (OL) was used. Thus, LV resulted as the simple sum of RC and AW signals, previously multiplied by suitable linear coefficients obtained after the IVM. The OL model is the most widely used in clinical applications.

Other methods could have been used for data collection, such as voluntary restriction (Strömberg et al., 1993; Strömberg, 1996), where the subject is asked to produce different breathing patterns at a time, one predominantly ribcage-controlled and another abdominally-controlled. This latter method is proposed as more suitable for untrained subjects, as it comprises more spontaneous manoeuvres than the IVM.

As for additional mathematical models, power, logarithmic and exponential functions have been used (Loveridge et al., 1983) and the results were reported as only marginally improving the accuracy of RIP. In our case, the OL model also provided acceptably accurate data with the eight subjects.

The main characteristics of the IVM are that it may require some training of the subjects, it involves simple computation and it may provide an immediate visual feedback of respiratory movements, particularly regarding the relative contributions of the ribcage and abdomen. While performing, the IVM could represent some difficulty to less experienced subjects; it was apparently a simple task for our professional subjects.

We estimated the individual contributions of the AW and the RC on the basis of IVM. Although the calibration concerns the conjoint effect of both these compartments, there seem to be no reason to doubt that the individual AW and RC can be determined with approximately the same accuracy as the overall lung volume in our experiment.

The blowing against a fixed resistance in task 3, proved to be a convenient and helpful addition to the procedure of data collection. Besides serving as a yardstick for the flow analysis, it provided dynamic information in a wide range of lung volume, as compared to the quasi-static and narrow-range characteristic of the IVM. As a further refinement of the technique, different resistances could be used that better match the instruments characteristics, thus offering the subjects more realistic expiratory conditions.

Artifacts

The curves obtained for the performance tasks occasionally presented irregularities, showing apparent volume increase during playing. On the other hand, the RIP curves obtained from the blowing against the fixed resistance were almost perfectly linear. The irregularities can be explained by different factors: pressure variations inside the thorax, body movements, particularly the trunk and the arms; contractions of non-respiratory trunk muscles affecting the RIP signals. These factors will be discussed below.

Compression

Compression seemed to be the most important factor, especially in instruments requiring high blowing pressures. The effect on the RIP signals are not exactly artifacts, since they at least partly represent true volume changes and would contain two factors, the decrease of air volume due to compression and the effects of high pressures on circulation reducing the return of blood to the thoracoabdominal region (McCool, 1995). In our experiment, we measured the volume variations for compressive manoeuvres during breathhold at different LV (task 1d). This should provide coefficients that might be applied for compensating the compression effects. For such compensation the blowing pressures need to be tracked during playing, e.g., by means of a thin pressure transducer inserted into the subject's corner of the mouth (Fuks and Sundberg, 1998). In our data, the ILV values were taken before compression took place, while the TLV data were affected by this compression.

Body movements

Body movements have been already reported and commented in our experiment. They might be divided into at least three categories: spine movements- flexion and torsion, arm movements and contraction of accessory respiratory muscles.

The measurement of the effect of arm movements on RIP LV, as shown in Figure 6, refers to just one of the possible modifications from a basic configuration. That kind of movement is the most common, although rarely performed all the way to 90°. Another important modification in body posture is related to the way of holding the instrument. Holding a bassoon for instance, an instrument of considerable proportions and weight, may invite to substantially varying body positions, which would affect the calibration. In such cases, it is recommendable to carry out the calibration with the instrument held in a typical playing position, as was done in the present investigation.

Contraction of certain accessory breathing muscles such as the sternocleidomastoid and some neck muscles may affect the accuracy of RIP measurements. The sternocleidomastoids are inactive in normal subjects breathing at rest (or even during our calibration) but are recruited when ventilation increases during exercise and under other challenging conditions (Delhez, 1974). Contraction of such muscles may show as an increase or a disturbance of the RIP RC signal which does not correspond to a LV change.

Respiratory behaviour

All of our eight subjects presented abdominal and ribcage movements that showed a positive correlation with the airflow during playing, i.e., both AW and RC were reduced in cross-sectional area during exhalation. The players presented what seemed to be characteristic respiratory patterns during playing; some had AW and RC movements that were performed in a parallel way, while others had more evident RC activity. In general, the flow curves showed a close similarity to the isolated RC curves.

The lung volume ranges used by the players seemed related to the blowing pressures required. At high lung volumes the recoil forces may produce relaxation pressures of 40 cm H_2O while at low lung volumes the relaxation pressures approach zero or even shift to negative. Consequently it takes a considerable muscular effort to create high lung pressures at low LV. Our results indicate that LV close to RV (0% VC) are not uncommon in some instruments. However, for the instruments requiring high blowing pressures, such as the oboe, LV below REL were rare. Thus, the oboists, in particular, seemed to take advantage of the recoil forces to create the blowing pressures needed. Moreover, it seems that a high IC/VC ratio may be advantageous in wind instrument playing, since it enlarges the LV range, which is associated with great expiratory recoil forces. Also, a sitting as opposed to a standing position stretches the IV/CV ratio to some extent and may therefore be favourable from this point of view. This might partly explain why some players prefer the sitting position during performance.

ILV values close to VC have sometimes been advocated as advantageous for wind instrumentalists (Stewart, 1987). Such values were rarely observed in our experiment. A reason may be that the demand for inspiratory efforts substantially increases at very high LV, sometimes even requiring the use of accessory muscles and spine movements. This may be uncomfortable. Also it should be kept in mind that wind instrument playing is not a question of producing high blowing pressures only. Some effects, such as staccato and vibrato tones, may require sudden activation of inspiratory muscles to reduce the blowing pressure, as observed in some flutists (Cossette, 1993). Alternating or simultaneous activations of the antagonistic expiratory and inspiratory muscles, which possibly is related to the much used though vague term “breath support”, may be difficult to achieve at very high lung volumes.

Almost every subject, when asked after the experimental session, had an established idea on how the inhalation and exhalation phases should be done under performance. The most common concepts being associated to starting inhalation with outward movement of the AW, while trying to keep that region in a mostly expanded position throughout playing. The action of the RC was generally reputed as deserving a secondary attention, and players agreed that trying to control playing mainly through RC would produce unsatisfactory musical results. These notions are also reinforced by several pedagogical works (e.g. Goossens, 1977; Teal, 1963; Bonade, 1962; Thurston, 1956).

Timing of breath pauses

The results in Table 4 showed good timing agreement between the audio breath pauses D_b and the inhalatory phases D_{RC} and D_{AW} of the RC and AW. However, the values for the offsets OS_{RC} and OS_{AW} averaged to approximately –50 ms, with minimum values of less than –160 ms. These negative values mean that inhalation was initiated slightly earlier than the interruption of the audio signal. Reverberation can be rejected as an explanation, because of the close microphone distance and the short reverberation time of the recording room, lower than 1.0 second. Repeated measurements of the time coordinates of breath pauses showed an error smaller than 15 ms. Also, the players did not use circular breathing, so no inhalation took place during playing. All data were recorded simultaneously into the digital multi-channel recorder, thus excluding systematic delays of any of the signals. Therefore, our results indicate that the AW and RC increases, presumably reflecting body movements, generally anticipated the audio pauses. Similar anticipation has been observed in other contexts of motor control, such as in lifting of objects and unloading of forces, where postural activity is started in advance to the main action, in the order of 100 ms (Hugon et al., 1982).

Comparisons with singing

Lately, respiratory data on singers have been published, which obviously are interesting to compare our results. Initially, it must be pointed out that subglottal pressures in singing are mostly considerably lower. Typical values for classical western singing are between 3 and 35 cm H_2O (Cleveland and Sundberg, 1985; Schutte, 1980) while in reed instruments it ranges between 10 and 110 cm H_2O (Fuks and Sundberg, 1996). Unlike the voice, reed woodwinds are clearly pressure-controlled systems (Benade and Gans, 1968). Also the airflow for voice production is usually considerably higher than in reed woodwinds.

Professional wind players and singers present highly systematic behaviour regarding subglottal pressure (Sundberg et al., this issue, 1998;

Schutte, 1980; Fuks and Sundberg, 1998). Also, singers are highly systematic with respect to ILV and TLV (Thomasson and Sundberg, 1997). We did not ask the subjects to repeat the same task so as to secure data on consistency, which, however, could be expected, at least in performances of well rehearsed pieces. The mode values of professional opera singers' ILV and TLV have been reported to be 70% and 30% VC (Thomasson and Sundberg, 1997). Our ILV and TLV data were not clearly different.

Those authors also found that during singing the AW made small movements, poorly correlated with the expiratory activity in four of their five singer subjects. In most of our wind instrument players the AW contributed importantly to the LV changes during playing in four players even more importantly than the RC. This is surprising, as an AW contraction can affect the thoracic cavity over a comparatively small area as compared to the RC.

Conclusion

The RIP method, as used in our experiments, revealed to be robust, non-invasive and accurate. The relationship between the output of the RIP equipment and lung volume, as corroborated by means of spirometry, was surprisingly linear for the typical range of reed woodwind instruments. Yet, artifacts were observed. One type of source is body and arm movements. To ensure an acceptable accuracy of measurement, the method requires the subject to keep a rather fixed body position, either sitting or standing. Also, the respiratory manoeuvres of maximal inhalation from FRC and RV and the IVM must be carefully done. Another type is lung compression, which produced important distortions in some cases. Such artifacts might be compensated for by post-processing of the data, provided the blowing pressures are recorded on an additional channel.

In our players ILV typically ranged between 55% and 87% of VC for all pieces. In instruments that require blowing pressures in the range of the relaxation pressures, i.e. up to 40 cm H_2O approximately, TLV achieved values as low as close to 0% VC in extreme cases. However, for instruments requiring higher blowing pressures such as the oboe, TLV values below REL were rarely observed.

During a highly demanding piece, from the point of view of respiration, inhalation pauses were typically about 300 ms long and synchronized with the increases of the RC and AW signals, the latter consistently showing a quick and continuous increase. The results of the investigation suggest that the RIP method, at least when complemented by spirometry and constant-flow procedure, should be useful for future research as well as for pedagogical purposes.

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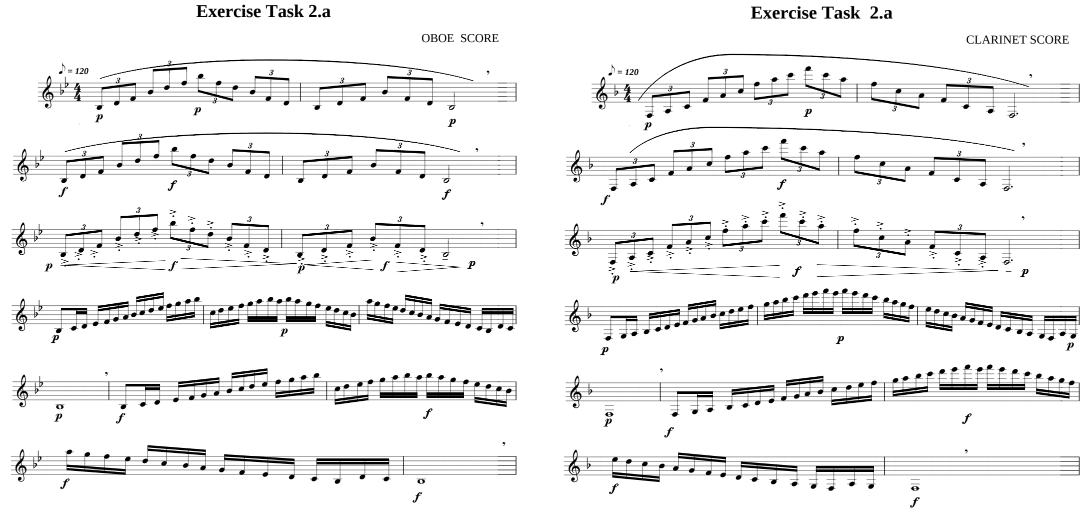
Appendix

Table 5. Respiratory profile of the subjects, as obtained during the respiratory manoeuvres in task 1. IC and VC were measured as described in the text. Expected values for VC, IC, RV, FRC and TLC, marked with (*), from statistical populational data as a function of height, age and gender ((Morris, 1971; Bates and Christie, 1964).

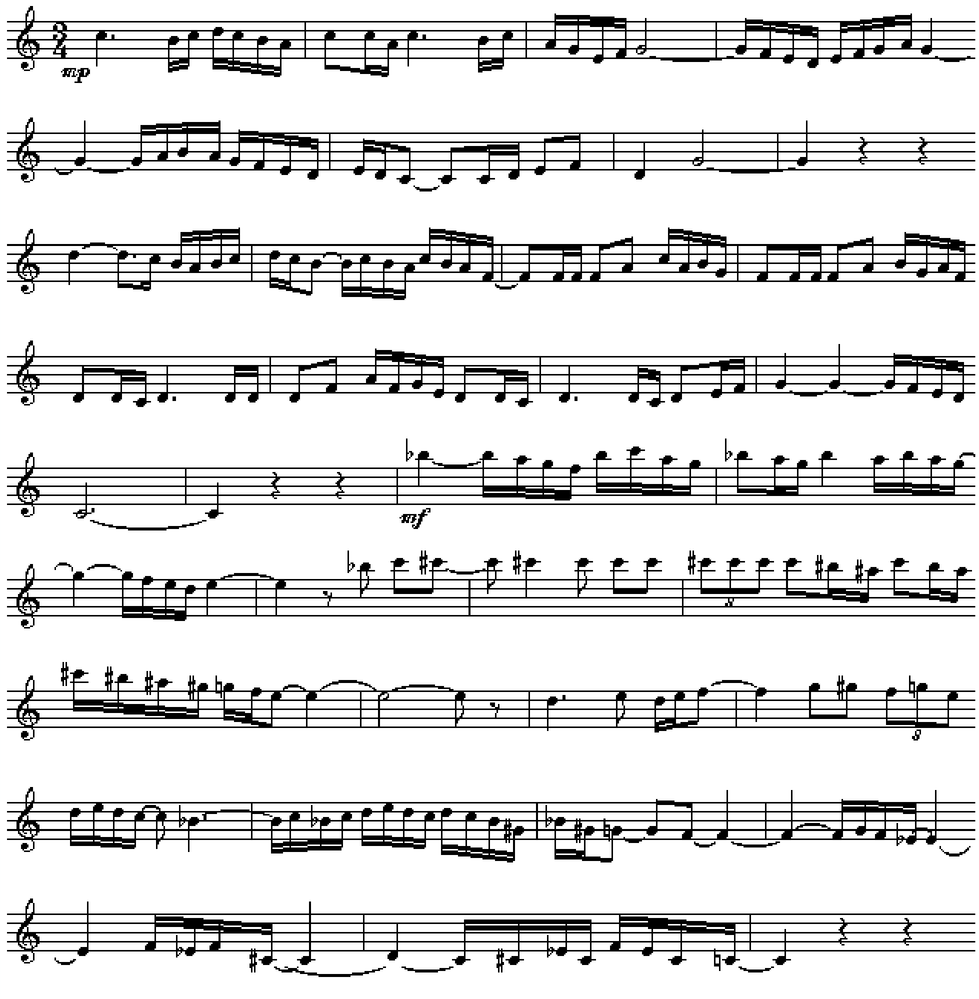
Subject	Max IC[liters]	Max VC[liters]	IC/VC [%]	Height [m]	Age [years]	Gender	weight	TLC*	FRC*	RV*	IC*	VC*
Ob1	4.6	5.9	77	1.85	41	M	86	7.83	4.33	2.29	3.5	5.54
Ob2	4.2	6	69	1.82	38	M	82	7.64	4.21	2.17	3.43	5.47
Cl1	3.2	5.2	62	1.85	35	M	89	7.88	4.33	2.18	3.55	5.7
Cl2	2.1	2.9	74	1.6	32	F	57	5.77	3.05	1.45	2.72	4.32
Sx1	3.7	4.8	78	1.79	48	M	96	7.14	3.95	2.18	3.19	4.96
Sx2	3.4	4.8	70	1.78	31	M	90	7.28	3.95	1.9	3.33	5.38
Bn1	3.4	4.9	67	1.78	37	M	70	7.23	3.95	2.01	3.28	5.22
Bn2	3.5	5.5	63	1.91	52	M	86	8.26	4.59	2.42	3.67	5.84



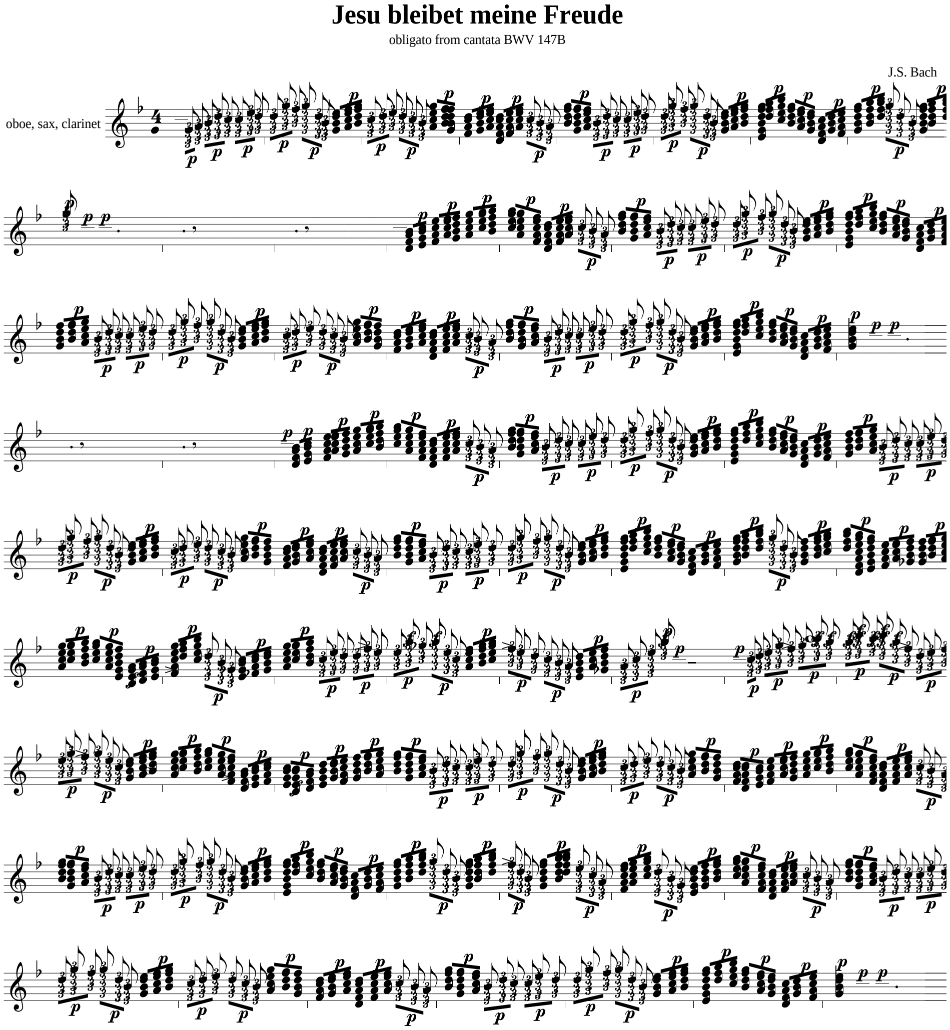
Score 1. Scale exercise covering the typical range of the instruments. The score on the left side was used for the oboe and the alto-saxophone (transposed a whole tone above, thus starting with a written C and sounding E♭ *Major). The sheet on the right was applied to the clarinet and to the bassoon, the latter transposed an octave and a fifth below, i.e., starting with a* $B\flat_1$.

Bolero

M. Ravel



Score 2. Solo part of Bolero *by M. Ravel. The same score, exactly as it is written, was used for the oboe, alto-saxophone and clarinet. For the bassoon, a version written one octave below was applied.*



*Score 3. Obbligato part of "*Jesu bleibet meine Freude*", from J.S. Bach's cantata BWV 147. The score version shown was applied to all instruments, with the exception of the bassoon, which followed a score written one octave below.*

Assessment of blowing pressure perception in reed wind instrument players

Leonardo Fuks[1]

Abstract

Perception of blowing pressures in eight reed instrument players was assessed by means of a psychophysical production method. The aim of the study was to investigate how the players judge mouth pressures independently from playing conditions, i.e., without embouchure effort, reed vibration, airflow or auditory feedback. Reference pressures were established by relaxation at three lung volume levels ranging between just above functional residual capacity (FRC) to nearly full lungs. Successive doubling estimates were employed to assess the relationship between pulmonary pressure - a physical variable, and perceived pressure - a psychophysical variable. Regression analysis was applied to the data under four different models - linear, logarithmic, exponential and power functions. Generally, the linear model was the one that presented a highest correlation with the experimental data (r^2=0.943), while the logarithmical model (Fechner Law) corresponded to a lowest correlation (r^2= 0.869). The power function exponents (Stevens Law, r^2=0.924) varied considerably among subjects, with a global average of 0.94, and among the three increasing lung volume levels, 0.79, 0.92 and 1.13, respectively. The method provided consistent data from the subjects and the results provided information about this rarely studied modality.

Introduction

At least two categories of professionals make use of skilful expiration in their work: wind instrument musicians and glass blowers. Some studies have focused on physical and physiological aspects of these otherwise dissimilar activities (e.g. Navrátil & Rejsek, 1968; Bouhuys, 1968; Schorr-Lesnick et al., 1985; Fuks & Sundberg, 1996). Wind instruments, according to the mechanism of sound generation, are classified as air-reed (e.g. flutes), lip-reed (e.g. trumpet), free-reed (e.g. harmonica) and mechanical - or simply reed instruments (e.g. oboe, clarinet, bassoon and saxophone). The present study refers to mechanical-reed instruments, which are pressure-controlled systems (Benade, 1968) and require a fine, dynamic but vigorous control of the player's respiratory apparatus. Typical values for blowing pressures usually range between 10 and 120 cm H_2O, according to instrument, melodic-articulatory design of the task and dynamic level required. A musical phrase may last, in extreme cases, for more than 40 seconds. The pauses between respiratory phrases, when the performer usually exhales residual air, rests and inhales for the coming phrase, may greatly vary from several seconds down to less than 300 milliseconds, also depending on the musical score (Fuks & Sundberg, 1998).

Professional players generally present a very systematic use of blowing pressure during trained tasks. Low deviations observed among repeated procedures, suggested that the control of the performance might be dependent on proprioception of blowing pressure, together with other factors. In order to control the vibrations of the reed and the acoustically-coupled air column, the player changes the input parameters such as the blowing pressure and the embouchure (Fuks & Sundberg, 1996). Embouchure consists of a constellation of forces and positions in the lip and mouth parts, directly affecting the reed behaviour and resulting sounds. Variations of sound pressure level, pitch and blowing pressure in actual performance are exemplified in Figure 1.

Respiratory control is mediated by a complex system that involves neural, psychological, chemical and mechanical interactions. The process of playing a wind instrument is therefore underlined by a mechanical sensorial apparatus consisting of different receptors located in the mouth and in the respiratory system. The lips in contact with the mouthpiece of the instrument and pressed against the teeth are a sensitive

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[1] UFRJ- Rio de Janeiro Federal University-School of Music, Rua do Passeio 98, 20021-290, Brazil

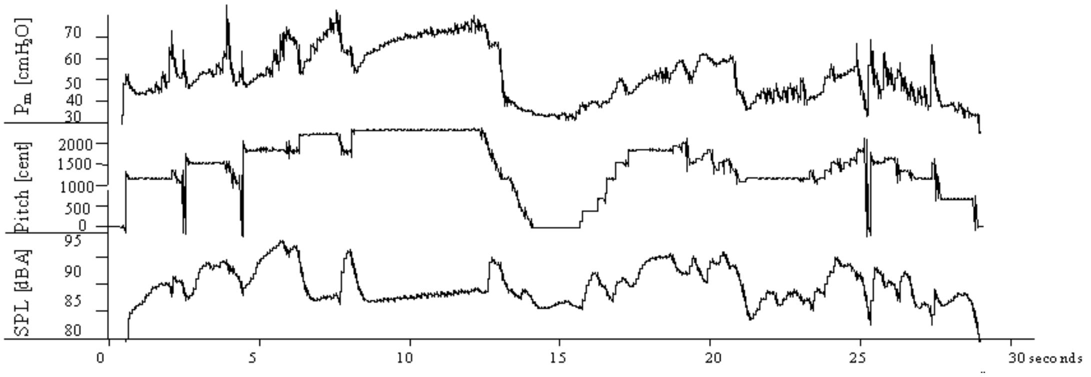


Figure 1. Sound pressure level (in dBA), pitch (relative to C4, in cents) and blowing pressure (P_m in cm H_2O) signals from a performance of J. Haydn's Oboe Concert in C Major, recorded by the author. The realistic data shows that there is no simple relationship between the three variables. Particularly in the oboe, it has been shown that blowing pressure usually increases both with dynamic level and pitch (Fuks & Sundberg, 1996).

large area of the brain cortex (Penfield & Rasmussen, 1950). The embouchure muscles, which are additionally responsible for sealing the connection to the reeds, may continuously respond to blowing pressure variations. The auditory feedback from the instrument and acoustic environment also provide relevant clues about the instrument behaviour.

Respiratory effort has been investigated in healthy and pathological cases, generally referring to inspiration, the most critical phase through a clinical perspective (e.g. Stubbing et al., 1983). Studies on perception of respiratory flow and pulmonary pressure have been carried out in healthy subjects, in spite of reporting ranges which are not realistic to wind instrument playing (Kayser et al., 1997; Stubbing et al., 1981; Muza et al., 1984). Expiratory effort, on the other hand, has not received much attention so far and the studies are mostly related to physical exercise at hyperpnea. In order to cope with the musical and instrumental demands, the performer establishes a breathing pattern that is usually outlined by short and deep inhalations followed by relatively long periods of exhalation, for which *hypopnea* (as opposed to hyperpnea) would be a suitable term. Other related studies dealt with static and dynamic perception of lung volumes and respiratory rate in healthy subjects (Katz-Salamon, 1983; Cherniak et al., 1988). Specifically in wind instrument players, sensation of inspiratory volumes and pressures has been investigated (Smith et al., 1990), where consistent differences were found as compared to age-matched non-musical controls. Playing a wind instrument requires accurate perception of lung volume but also sensitive control of lung volumes through inspiratory and expiratory muscular contractions (Smith et al., 1990). Exhalatory flow can be produced by a combination of respiratory muscle contraction, passive recoil forces of the thorax and also gravity effects on the body. For full lungs, relaxation expiratory pressures of as much as 40 cm H_2O are developed, which would not require any active exhalation for such pressure. For a lung volume that corresponds to the functional residual capacity (FRC), the recoil forces of the rib cage are in equilibrium with the elastic forces of the lungs, resulting in a null relaxation pressure. Further down in lung volume, the relaxation pressures become negative. Diaphragmatic activity is also reported as taking place during exhalation in players, as a means of counterbalancing the expiratory forces and ensuring a fine control of the exhalation pressure and flow (Bouhuys, 1964).

In the actual playing situation the sensation of blowing pressure obviously is not the only relevant component for tone control. Other factors of relevance would be sensation of airflow, of contraction of lip muscles, and of the oscillations of the reed in the mouth. Also of importance may be the sound produced in the instrument which interacts with the resonating properties of the vocal tract, establishing vibratory states that are probably sensed by the baroreceptors and other sensitive structures involved (Benade, 1986).

The aim of the present study was to describe how the players judge mouth pressures independently from playing conditions, i.e., without embouchure effort, reed vibration, airflow or auditory feedback.

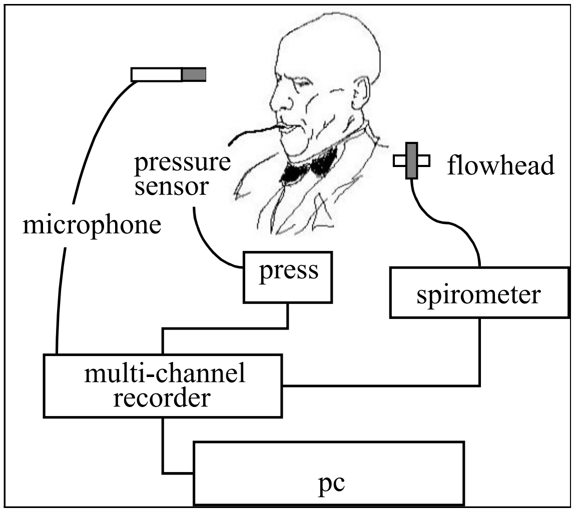


Figure 2. Experimental setup. A pressure sensor (Gaeltec CTO-2), was inserted in the subject's mouth for the tasks. The signals from the amplifier (press) were continuously logged by a multichannel TEAC PCM DAT recorder. A spirometer was used during controlled inhalation through the flowhead (F100L), measuring the lung volumes V2 and V3. The audio signal, for documentation purposes, was captured by a microphone. The experimental data was eventually ported to a personal computer for data processing, using Swell® and Excel® programs.

Materials and method

Eight professional musicians of four instruments, two clarinet, two saxophone, two oboe and two bassoon players, took part in the experiment as subjects. The setup for the experiment, consisting of a thin pressure sensor (Gaeltec CTO-2 strain gauge catheter, 2mm diameter; Gaeltec S7b amplifier), pneumotachograph (Silverman-Lilly type, Mercury CS-5, F100L flowhead), microphone (used for documentation), multichannel TEAC PCM DAT recorder and personal computer for data management, is shown in Figure 2.

The procedure, as described below, was preliminarily run having the author as subject with the help of an assistant to evaluate the experimental design. As the author is a professional wind player, his respiratory behaviour was expected to represent that of a typical trained subject. The time limit of the whole test was considered relevant, and the experimental protocol comprised three single-breath pressure sequences, at three different levels of lung volume.

The experiment took place in an ordinary room after a minimum of 30 minutes warming up period, during which the subjects played orchestral excerpts and solo parts with their instruments, as part of an experiment on respiratory patterns in performance (Fuks & Sundberg, 1998). As an initial phase of the experiment, the pneumotachograph was used for determining the subjects' lung volumes, namely the vital capacity (VC) and inspiratory capacity (IC) (Figure 3), through repeated respiratory manoeuvres, a procedure described elsewhere (Fuks & Sundberg, 1998). The subjects' respiratory profile, in terms of VC and IC, and additional data are shown in Table 4 in the Appendix.

To achieve volume V_1 (Figure 3), the subjects were instructed to hold breath at the end of the inspiration phase during relaxed breathing, when the lungs are filled with a volume that equals the tidal volume (V_T) plus the functional residual capacity (FRC). The pressure trans-

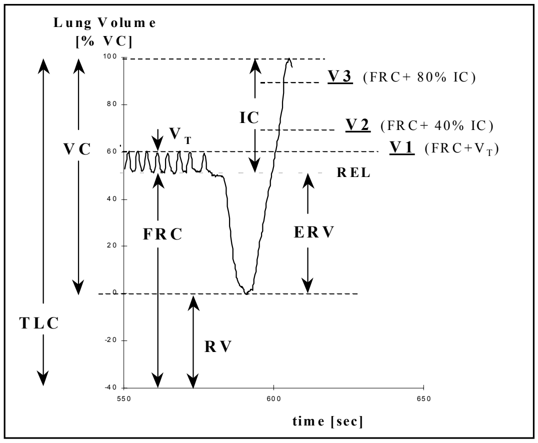


Figure 3. Relevant standard spirometric parameters: vital capacity (VC), total lung capacity (TLC), inspiratory capacity (IC), tidal volume (Vt), expiratory reserve volume (ERV), functional residual capacity (FRC), residual volume (RV) and the respiratory base-line represented by the resting end-expiratory level (REL). The three test volume levels, V1, V2 and V3 are also indicated.

ducer was brought by the subject into the mouth while its output signal was continuously recorded. At this initial lung volume, the sensation relative to relaxation pressure was assigned a value 1 (reference unit). A succession of verbal commands was followed, in random order, requiring the subject to produce lung pressures whose perceived magnitudes were one, two or four times the reference unit.

For volumes V_2 and V_3, the subjects attained FRC after a resting period of less than two minutes and inhaled through the meter flowhead a volume of 40% IC and 80% IC, respectively (Figure 3). The same procedure as for V_1 was then followed.

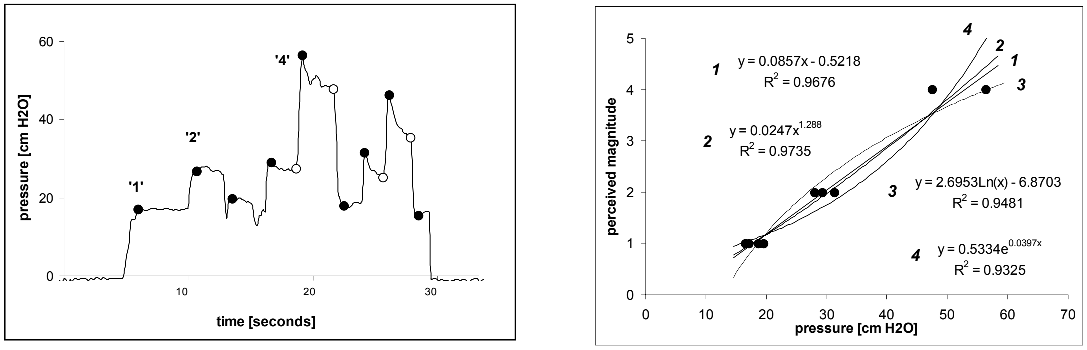
The time interval among verbal commands ranged between 2 and 4 seconds, and the duration of each sequence was set by the subjects, as they interrupted the task when starting to feel discomfort with the prolonged breathhold. Subjects were instructed to concentrate on the perception of pressure rather than on the effort to produce it. They were asked not to let any air escape and to maintain an open glottis, ensuring communication between mouth and lung, thus preventing pressure increase by action of mouth and other intraoral muscles. The whole experiment was carried out in standing position. The subjects, who got paid for their participation, were only informed that the experiment referred to the perception of blowing pressure.

Analysis and results

The data from the experiments, converted into SMP format, were initially analysed by means of the SWELL® signal processing software package. In most cases the pressure curves produced by the subjects presented a pattern of an initial value immediately followed by a decrease to a more stable level, usually within an interval of approximately two seconds, as shown in Figure 4a. For each pressure produced as a response to the verbal commands, onset and accommodation values were annotated. The data from each take were processed into three different groups: (1) all data points, (2) onset values of pressure, p_o, at each new instruction, and (3) the accommodation pressure values, p_a. When a pressure value did not significantly vary in a given sequence (within 2.0 cm H_2O variation), the same value was present in the three data groups.

At least three valid takes were produced for each lung volume per subject, the total of nine sets of experimental data, described in detail in Table 2, Appendix. The table shows, for each subject, the sequences performed at each volume (V1, V2 and V3), initial, minimal and maximal pressures produced. The initial pressures and ranges varied considerably among subjects and, in some cases, within subjects. For subjects 3, 5 and 6, the initial pressure levels were more separated among the three different lung volumes. In other subjects, however, these distinctions were less clear, including cases when the initial pressures at higher lung volumes achieved lower values than at lower volumes. In general, the initial pressures occurred between 2.0-17.0, 7.0-20.0 and 7.5-35.0 cm H_2O for V1, V2 and V3, respectively. The corresponding pressure spans among perceived magnitudes 4 and 1 ranged considerably between 18.5-92.0, 15.5-87.0 and 22.0-87.0 cm H_2O, for V1, V2 and V3, respectively.

The initial pressures at unit reference sensation were expected to reflect the relaxation pressures for each lung volume. In general, the initial pressure increased with lung volume.



Figures 4a and 4b. A typical pressure curve for the experimental task (sequence '121241241'). The onset (p_o) and accommodation pressures (p_a), are indicated by filled and empty circles, respectively. In Figure 4b, produced stimulus s, in cm H_2O, versus perceived magnitude, P. Regression line equations, according to Equations 1-4, are also presented.

However, some particular variations were observed for that value, as can be seen in Table 2, Appendix. For instance, subject 8 presented similar initial pressures at V3 and at V2; subject 1 produced higher pressures at V1 than at V2. Also, most of the subjects tended to slightly reduce the pressure values for each instruction as the sequence continued. In some cases, however, the pressure values even increased with the test progression.

The analysis comprised the calculation of the regression coefficients and determination index, r^2, for the four different models: linear, logarithmic (Fechner, 1877), exponential and power functions (Stevens, 1957) as shown by Equations 1-4, see Figure 4b for an example. The Excell® program was employed for computing the coefficients *a* and *b* for the following expressions:

Linear

$$P = a_L + b_L . s \qquad \text{Equation 1}$$

Power Function (Stevens)

$$P = a_P . s^{b_P} \qquad \text{Equation 2}$$

Logarithmic (Fechner)

$$P = a_F + b_F . \ln s \qquad \text{Equation 3}$$

Exponential

$$P = a_E . e^{b_E s} \qquad \text{Equation 4}$$

where P is the perceived magnitude (1, 2 or 4, according to the commands in the experiment),

s the pulmonary pressure stimulus, measured in the mouth, in cmH_2O,

a is an offset (Eqs. 1 and 3) or a multiplication constant (Eqs. 2 and 4),

b refers to the proportionality (Eqs. 1 and 3) or exponential (Eqs. 2 and 4) factors between P and s.

The linear function, Eq.1, describes the simplest relationship between stimulus and sensation. The power function, Eq. 2, refers to Stevens's psychophysical law (Stevens, 1957, 1975), where a_p is a constant and b_p is power-function exponent, PFE. The logarithmic function, Eq. 3, refers to Fechner's psychophysical model, which states that the perception of a continuum (stimulus) is proportional to the logarithm of the magnitude of the respective stimulus, plus a constant (Fechner, 1877). The exponential function, Eq. 4, is the inverted case of the logarithmic model, as it equates the logarithm of the perception with the magnitude of the stimulus. The determination index r^2 was obtained by the least squares method in each case, to compare the goodness of fit among the models. Such between-models comparison is not uncommon in respiratory psychophysical studies such as by Katz-Salamon (1984), who addressed subjective magnitudes of ventilation parameters. It should be borne in mind, also, that a poor replicability of the pressures produced at a given sensation level will reduce the determination index.

As mentioned above, the data were processed in three different forms of grouping concerning onset and accommodation values. One-way ANOVA was performed with the r^2 coefficients obtained from each model according to the three types of data grouping and no statistically significant difference was found ($p>0.40$ in all cases). This means that it was equivalent to consider onset or accommodation values of pressure, in terms of fitness of data. However, there were differences in the coefficients *b* corresponding to each model, as onset values were consistently higher than accommodation ones. For example, the average PFE values were 0.94 and 1.10 for the onset and accommodation groupings, respectively. It is clear from Eqs. 1-4 that larger ranges of pressure, represented by *s*, will correspond to lower *b* values. It is reasonable to assume that the onset pressure values reflect the most spontaneous response of the subjects after hearing each command. Therefore, we will refer exclusively to the onset values of pressure in our results.

The coefficients ***a*** and ***b*** for the four types of regression (Eqs 1 to 4) at each lung volume level per subject are presented in Table 1a and 1b, respectively. In order to reduce the amount of data displayed, the coefficients from the three trials were arithmetically averaged and the mean value and standard deviation are presented. In our analysis, we will concentrate on the ***b*** coefficients, as they are more meaningful to our purpose of assessing sensitivity. In general, a wide range for the coefficient values was found among the eight subjects and under the four models. They will be presented and commented separately. The determination coefficient (r^2) from all regressions, averaged between the three takes at every volume level, are presented in Table 3, Appendix.

*Table 1a and 1b, respectively, presenting **a** and **b** coefficients calculated from regression of data points, according to Equations 1 (linear), 2 (power function), 3 (logarithmic function) and 4 (exponential function). Values were averaged from three different takes at each lung volume level, see Table 2 in the Appendix. In parenthesis, the standard deviations between the takes.*

subject	model	**a** coefficients		
		V1	V2	V3
1	linear	0.075 (0.518)	-0.120 (0.070)	-0.092 (0.397)
	power	0.117 (0.085)	0.065 (0.015)	0.041 (0.020)
	log	-4.454 (2.127)	-4.942 (0.345)	-6.116 (0.970)
	exp	0.758 (0.197)	0.661 (0.034)	0.665 (0.128)
2	linear	0.827 (0.057)	0.656 (0.189)	0.303 (0.077)
	power	0.488 (0.014)	0.493 (0.243)	0.149 (0.086)
	log	-0.348 (0.271)	-0.706 (1.303)	-3.099 (1.157)
	exp	0.949 (0.071)	0.910 (0.079)	0.770 (0.012)
3	linear	-0.225 (0.094)	-0.148 (0.367)	0.015 (0.079)
	power	0.087 (0.004)	0.120 (0.091)	0.083 (0.019)
	log	-3.855 (0.116)	-3.854 (1.891)	-4.135 (0.578)
	exp	0.580 (0.017)	0.628 (0.100)	0.665 (0.032)
4	linear	0.429 (0.200)	0.397 (0.104)	-0.039 (0.300)
	power	0.281 (0.141)	0.233 (0.043)	0.082 (0.036)
	log	-1.708 (1.379)	-1.798 (0.840)	-3.966 (1.712)
	exp	0.79 (0.011)	0.749 (0.039)	0.616 (0.111)
5	linear	0.618 (0.061)	-0.627 (0.099)	-1.921 (0.276)
	power	0.641 (0.047)	0.032 (0.004)	0.002 (0.001)
	log	-0.007 (0.136)	-6.576 (0.146)	-11.574 (2.025)
	exp	0.920 (0.043)	0.515 (0.031)	0.232 (0.089)
6	linear	0.238 (0.457)	0.201 (0.071)	-0.378 (0.036)
	power	0.150 (0.100)	0.078 (0.009)	0.015 (0.002)
	log	-2.818 (0.799)	-3.793 (0.785)	-7.585 (0.301)
	exp	0.708 (0.259)	0.685 (0.123)	0.557 (0.005)
7	linear	-0.311 (0.119)	-0.346 (0.211)	-0.912 (0.194)
	power	0.104 (0.038)	0.092 (0.025)	0.028 (0.010)
	log	-3.784 (0.977)	-4.071 (0.568)	-6.616 (0.890)
	exp	0.571 (0.025)	0.564 (0.062)	0.440 (0.027)
8	linear	0.242 (0.523)	0.358 (0.078)	0.288 (0.114)
	power	0.313 (0.191)	0.229 (0.052)	0.273 (0.186)
	log	-1.614 (1.880)	-2.122 (0.720)	-1.980 (1.285)
	exp	0.722 (0.170)	0.807 (0.015)	0.772 (0.048)

subject	model	**b** coefficients		
		V1	V2	V3
1	linear	0.086 (0.005)	0.103 (0.014)	0.062 (0.016)
	power	1.003 (0.249)	1.131 (0.045)	1.125 (0.163)
	log	2.159 (0.473)	2.383 (0.075)	2.392 (0.301)
	exp	0.038 (0.002)	0.047 (0.006)	0.028 (0.008)
2	linear	0.043 (0.010)	0.043 (0.004)	0.037 (0.003)
	power	0.449 (0.013)	0.458 (0.158)	0.709 (0.147)
	log	0.814 (0.127)	0.912 (0.348)	1.416 (0.310)
	exp	0.024 (0.012)	0.020 (0.002)	0.018 (0.001)
3	linear	0.107 (0.029)	0.071 (0.014)	0.059 (0.004)
	power	1.023 (0.065)	0.888 (0.243)	0.908 (0.066)
	log	1.999 (0.145)	1.807 (0.562)	1.822 (0.170)
	exp	0.053 (0.014)	0.034 (0.006)	0.029 (0.002)
4	linear	0.074 (0.012)	0.062 (0.005)	0.065 (0.009)
	power	0.674 (0.167)	0.673 (0.064)	0.948 (0.138)
	log	1.296 (0.533)	1.260 (0.341)	1.794 (0.537)
	exp	0.039 (0.006)	0.033 (0.006)	0.035 (0.008)
5	linear	0.121 (0.015)	0.128 (0.005)	0.116 (0.016)
	power	0.508 (0.036)	1.355 (0.049)	2.062 (0.266)
	log	1.031 (0.058)	2.925 (0.044)	3.880 (0.555)
	exp	0.056 (0.008)	0.058 (0.004)	0.063 (0.021)
6	linear	0.064 (0.014)	0.044 (0.002)	0.043 (0.001)
	power	0.860 (0.274)	0.882 (0.029)	1.218 (0.039)
	log	1.529 (0.179)	1.631 (0.268)	2.449 (0.087)
	exp	0.035 (0.016)	0.024 (0.007)	0.021 (0.001)
7	linear	0.152 (0.019)	0.124 (0.006)	0.130 (0.011)
	power	1.091 (0.139)	1.050 (0.081)	1.366 (0.114)
	log	2.210 (0.391)	2.169 (0.152)	2.844 (0.308)
	exp	0.073 (0.009)	0.058 (0.004)	0.061 (0.003)
8	linear	0.115 (0.031)	0.089 (0.007)	0.090 (0.006)
	power	0.756 (0.293)	0.755 (0.095)	0.720 (0.215)
	log	1.402 (0.690)	1.514 (0.284)	1.438 (0.453)
	exp	0.062 (0.016)	0.042 (0.003)	0.043 (0.002)

Linear model

The linear model presented the highest average determination index among all, $r^2 = 0.943$ (Table 3 in the Appendix), but the slope, i.e. b_L in Eq. 1, varied considerably between subjects and conditions, between 0.037 and 0.152, a ratio of more than 400% (Table 1b). Obviously, the scales used affected the coefficient's absolute values, but not the ratio between them. This applicability of the linear relationship, indicating a direct proportionality between variation of perceived and actual pressures, is somewhat surprising, as for many other psychophysical modalities a linear model has been shown to be inadequate (Stevens, 1975), see the Discussion section. ANOVA was applied to all linear coefficients with respect to the volume level factor (V_1, V_2 and V_3) and no statistically significant effect was found ($p>0.50$). This indicates that for the linear model, the lung volume level does not affect sensitivity of blowing pressure in the whole group.

The ***a*** coefficients represent an offset in the linear function, and the total average was -.002 (s.d. 0.416). This indicates that zero values in the stimuli and perception are approximately coinciding in most of cases. However, ***a*** reached unexpected values in some cases. Subject #5, for instance, presented an ***a*** coefficient of -1.921 at V3, what seems to be a considerable deviation as compared to the two previous V levels (Table 1a).

Power function (Stevens Law)

The global average value for the determination coefficient r^2 for the PFE values, i.e., b_P in Eq. 2, was 0.924. Some subjects, such as #1, #4, #6 and #7 presented values for r^2 that were consistently above 0.90 (Table 3, Appendix). A one-way, repeated measurements ANOVA, reveals that there is no significant effect of lung volume on r^2 ($p > 0.37$). This means that there was no difference in the goodness of fit for the subjects' performance among volumes V1, V2 and V3.

Generally, PFE varied between 0.45 to 2.06 according to subject and lung volume, as shown in Table 2 in Appendix, with a global arithmetical average of 0.94. One possible cause of this variation was vital capacity. The PFE data were plotted against VC for all subjects and the correlation between both variables was insignificant (R=-.0054), indicating that the lung capacity is not a factor in the pressure sensation PFE. With some subjects, there was a trend of PFE increase with lung volume, while in others it was not apparent. The whole group average, standard error and standard deviation values for PFE were 0.79 (s.e.=0.05; s.d.=0.27), 0.92 (s.e.=0.05; s.d.=0.30) and 1.13 (s.e.=0.08; s.d.=0.42), for V1, V2 and V3, respectively. If subject number 5, who presented much greater variations in PFE than the others, is excluded from the group, the values for PFE are 0.84 (s.e.=0.06; s.d.=0.27), 0.82 (s.e.=0.05; s.d.=0.26) and 1.00 (s.e.=0.06; s.d.=0.26). There was no significant variation in PFE between V1 and V2. However, the highest volume (V3) involved statistically significant increase of PFE compared to the lower ones (one-way Anova, repeated measurements, $p<0.05$). This result somehow contradicts the linear model, where no effect of volume level was found, see above.

It has been argued that errors are induced when using arithmetical mean for averaging PFE, a common procedure in psychophysical studies (Van Doren, 1996). Therefore, all the exponents were also converted into angles (arctangent function), then averaged and reconverted to PFE values. This procedure yielded a global FPE of 0.88 instead of 0.94, and the effects of volume level, discussed above, remained unchanged. Proceeding so, averages were reduced to 0.76 (s.d.=0.17), 0.84 (s.d.=0.18) and 1.05 (s.d.=0.18) for V1, V2 and V3, respectively, for all subjects. It is important to note that the angular averaging procedure tends to provide results generally lower for PFE than the arithmetic average. In any event, it seems fair to conclude that the PFE values were generally somewhat lower than one.

Logarithmic model (Fechner Law)

For this model, the average value for r^2 throughout the subjects and lung volumes is 0.869, according to Table 3, Appendix. The b_F coefficients (Eq.3) were found within a wide range between 0.81 and 3.88, using natural logarithm for the calculations. The relationship between the logarithmic coefficients with the PFE is not necessarily linear, but positively correlated. For our experimental data, an unexpected quasi-linear relation has been established, so that

$$\text{PFE} = 0.484 * b_F + 0.0034,\ r^2 = 0.9761$$

where B_F is the logarithmic coefficient, see Equation 3.

Exponential

The determination coefficient, r^2, presented a global average of 0.932, which is slightly better than the power function and definitely better than the logarithmic function. Exponential coefficients, according to Eq. 4, ranged between 0.020 and 0.073. The use of such a coefficient is not established in psychophysical studies, however.

Discussion

The method

Our method is that of ratio production by judgement doubling (Stevens, 1975). In a typical production test, the subject is usually allowed to adjust the stimulus, usually produced by an external system, to meet a prescribed ratio. Although the task of assessing the perception of intrapulmonary pressure is complex, the production test approach applied seems particularly suitable for the present investigation. The alternative of inflating the subjects with externally generated pressures and having them rate these pressures would require that the subjects either keep a constant muscular tension or that they be completely relaxed. Both these situations would be unrealistic, at least to a wind instrumentalist. Also, the sensations of internally generated blowing pressures are very different from externally generated pressure. Rating stimuli as numbers which are powers of two was deemed as natural by the subjects, in contrast with the judgement with sequential integer numbers, previously tried in a pilot experiment. However, the doubling of the perceived sensation in practice achieved the limit of 4, due to the fact that the pressures at that point were already comparatively high (global mean 54.5, s.d. 23.5), reaching extreme values of more than 100 cm H_2O in some subjects. A drawback was that the investigation was limited to three pressure levels that could be used. Also, the test is confined to the calculation of regression coefficients between the stimuli and sensations. It does not provide any estimates about the difference thresholds involved, which corresponds to the amount of change in stimulus required to produce a just noticeable difference (jnd). This could hardly be achieved with a production test.

The wide variation observed in PFE is probably due to the combination of legitimate inter-individual differences with structural characteristics of the test. As no limits are proposed for the pressures to be produced by the subject and a fixed range between one and four is defined for the sensation, significant variations could be expected. If the subject tends to exaggerate in the production of internal pressures, the power exponents would naturally tend to be lower than if the subject assumes a more discrete range. On the other hand, it has been argued that limiting the range of the stimuli introduces biasing in the judgements, at least for loudness perception (Warren, 1970).

Related psychophysical studies

It is still a controversial point whether or not individuals are able to fully distinguish between the force generated and the sense of effort required in muscular contraction, particularly when muscular fatigue or other limitations on maximum voluntary contraction are present (Gandevia et al., 1981; Stubbing et al., 1983). However, psychophysical scaling functions for both perceived effort and generated force seem particularly systematic and stable for several kinds of muscular-demanding activities, especially in isometric exercise (Stevens, 1974, 1989). Stevens' power law has been found to be a very accurate expression of the relationship between stimulus magnitude and the associated sensory magnitude, in most psychophysical experiments covering a wide gamut of modalities (Gescheider, 1985). In our experiment, PFE for intrapulmonary pressure sensation varied between 0.36 and 2.06, depending on subject and lung volume, the overall mean value being 0.95. Some typical values for PFE's, as reported by Stevens (1975), are: pressure on palm (1.1), muscle force (1.7), 60 Hz vibration in finger (0.95), tactual hardness (0.8), and vocal effort (1.1). These data were mostly obtained by use of cross-modality comparison techniques, i.e., a method in which the observer equates the sensation magnitudes produced in two different modalities, not requiring from the subject any kind of numerical judgement. It is interesting that our mean value of PFE was similar to that reported for vocal loudness, which is controlled by lung pressure (Schutte, 1980). The work involved in playing reed woodwinds may be approximated to an isometric model, as the movements are slow and the muscular tension may be great. Van Doren (1996) found power function exponents for hand isometric force between 0.75 and 0.80 by means of halving and doubling judgements.

Perception of loudness, which musicians are very familiar with, has been largely investigated. However, it has been shown that loudness assessment may be susceptible to bias effects such as the first stimulus presented, the range of stimuli presented, the instructions to the subjects, the range of permissive responses, factors related to experience, motivation, attention and others. Very large inter-individual differences have been observed and consistent results are usually only obtained by averaging judgements of a large number of subjects (Warren, 1970; Poulton,1979). For instance, Fletcher found a PFE of 0.3 by a method consisting of comparing binaural to monaural listening; Stevens also reported a 0.3 value which became an international standard for the sones scale (Gescheider, 1985); Zwicker & Fastl (1990) obtained the same 0.3 for pure tones and 0.23 for uniform exciting noise, using doubling and halving methods. Warren (1981) reports a considerably higher exponent of 0.5 obtained with a large group of subjects. Considerable inter-individual differences have been documented by Schneider (1981), where five subjects showed exponents varying between 0.22 and 0.56 (mean 0.44, s.d. 0.14). Our eight subjects' PFE values for pressure perceptions did not vary more than Schneider's loudness exponents, being the s.d. /mean ratio considered.

In an experiment of pressure magnitude estimation, using inspired pressures (negative manometric pressures) controlled by the experimenter, Smith and co-workers (Smith et al., 1990) found exponents of 1.34 (s.d.=0.14) and 1.06 (s.d.=0.09) for wind musicians and controls, respectively. That difference between groups, obtained from a group of 13 professional players and 13 age- and sex-matched controls, was significant and the authors suggested that a similar situation would take place with expiratory pressures. Our experiment was done through a different method, with a smaller group and, apparently, non-players would hardly serve as controls, as the tasks would need the specific expiratory ability or at least a long period of coaching. The values found in the present study for the power exponent PFE, averaging between 0.82 and 1.00, were generally lower than those reported (Smith et al., 1990) for the inspiratory task. This is not surprising: for negative pressures production, the range is usually considerably narrower and the extreme values are achieved more easily and probably in a more reproducible way (Vincken et al., 1987). This suggests that the subject will adjust the range of sensations in a smaller range of inspiratory pressures, therefore with a higher power exponent. Also, the production of negative and positive pressure involves different mechanical, muscular and nervous work; therefore the sensitivity would not necessarily be the same.

Effect of volume

The increase in sensitivity between the lowest volumes and V3 may be due to the actual recruitment of additional pressure-sensitive elements, but also to the fact that pressures generally increased with lung volume and some extremely high values were prevented by a downward flattening of the pressure curve. This might cause an increase on the calculated power exponent. It is important to note that at high expiratory pressures, the Valsalva manoeuvre takes place, considerably changing the subject's sensations and expanding the sensory region to a much wider area of the body, as for instance neck, head and upper limbs (Sharpey-Schafer, 1965). Another possible change in sensation refers to the fact that the subject may start to judge muscular effort in a broader sense than just the self-produced expiratory pressure. A study by Salamon (1976) showed that the exponents (according to Steven's model) for volume perception at lung volumes above FRC were smaller than for volumes below FRC. This could somewhat apply to the perception of lung pressure. Our study, however, indicated that the perception of intrapulmonary pressure is positively correlated to lung volume, at least between values just above FRC and near-full lungs. Reproduction of initial pressures was not consistent for some subjects, mainly at V_1. This indicates that, as lung volumes were carefully produced, the initial pressures did not precisely reflect the static relaxation pressures. One possible reason is that some subjects might have closed the glottis, while increasing pressure by contraction of muscles in the mouth. A method for preventing this might be through providing feedback of glottal closure to the subjects, sensed by an electroglottograph (EGG) device. An additional procedure is to have the subjects blow through a mouthpiece with a small orifice that causes a low but continuous airflow that would ensure open glottis; however, the lung volume would no longer be kept constant throughout the task. Tack and co-workers (1983) have shown that changes in lung pressure and volume produce changes in sensation. Cherniack and co-workers (1987) suggest that both variables, which are directly related to the work of breathing, provide information to the respiratory control so that it can work under optimised conditions of comfort and energy consumption. The observed increase in sensitivity with lung volume level in most subjects may be the result of a superposition of both pressure and volume stimuli, which are sensed by some common mechanoreceptors, mainly tendon organs which are also reported to modify medullary respiratory neurons (Shannon et al., 1987).

The tested lung volume levels ranged between FRC and full lungs. It would be interesting to include volumes lower than FRC in future experiments. However, breathhold times are reduced and expiratory effort considerably increased with volume decrease. This limits the number of data points per task.

Dyspnea

Another limitation was that each take had to be done during one single breathhold. This limited the amount of pressure recordings during the takes. For reasons of comfort, the subjects were instructed to stop the sequence when they experienced dyspnea although, in real performance, wind instrumentalists might continue beyond that point. Killian et al. (1982) have shown that the sensations experienced by subjects made to inhale on elastic and resistive loads vary quantitatively both with the changes in mouth pressure and time, with pressure having a coefficient of 1.36 and time a coefficient of 0.57. In our data, the pressures corresponding to each command tended to slightly decrease as the sequence evolved. It could hardly be said that the tasks would produce fatigue in the subjects and, as they were instructed to interrupt the sequence in case they felt discomfort, dyspnea did not play a significant role in our experiment. As a consequence, the time factor can be excluded from our considerations in this study. On the other hand, since the players were concentrated on the pressure variation task, this might extend the tolerable limits of comfort, as compared to tasks dealing exclusively with breathhold times and sensations (Lin, 1987; Alpher et al., 1986; Chonan, 1990).

Classes I and II Continua

Stevens & Galanter (1957) divided perceptual continua into two classes, prothetic (Class I) and metathetic (Class II), essentially based on a quantitative-qualitative dichotomy of the stimuli's nature. For instance, sound loudness and duration perceptions would belong to the first class, while pitch and proportion to the second. At the physiological level, it is proposed that Class I are additive while Class II are substitutive, in terms of the complex of receptors that sense the stimuli. For a wide-range increase of intrapulmonary pressure, different groups of muscles of the abdomen and the thorax are progressively recruited, according to the intensity of the pressure and the body configuration defined by posture and lung volume. This suggests that the blowing pressure continuum is of a Class II nature, in the sense that it deals with different receptors taking over the function of others, but also involves the additive mechanism of Class I, as long as a single receptor is exposed to stimuli of varying intensity.

It was found that in Class I continua the category scales are concave downward when plotted against a ratio scale of the subjective magnitude. On the other hand, Class II continua might be linear when so plotted. Our data has a better fit with the linear model in almost all subjects and tasks. This reinforces the hypothesis of the blowing pressure continuum belonging to Class II. Furthermore, the $\boldsymbol{a_L}$ coefficient from the linear regression seems to be a useful index to indicate some spurious data, as it is expected to be in average close to zero. In subject #3, there were reasons to considering the exclusion both due to a_L and b_P values.

Alternative methods

Other methods could be applied for assessing blowing pressure sensation. Cross-modality comparisons (Stevens, 1957, 1975) in which two different continua are compared, one of them being well known in terms of PFE, may be applied on further studies. Stevens made frequent use of acoustical stimuli, as mentioned above, consisting of both noise and pure tones, for the assessment of different perception modalities. Therefore, acoustical input for musical subjects would be a natural choice. However, care should be taken with such a procedure, as wind players might tend to process the auditory input in terms of the performance technique used in their instruments. It has been shown that blowing pressures are related to dynamical levels in a complex and apparently paradoxical way, according to instrument and pitch (Fuks & Sundberg, 1996). For instance, playing a piano tone may in some cases require a higher blowing pressure than playing a forte tone. Another factor of relevance might be the inter-individual variations in the loudness power exponents, already discussed. The cross-modality comparison could be validated with an independent evaluation of the subjects' loudness perception. Another kind of experiment could consist of eliminating the player's acoustic feedback from the instrument, e.g., by masking noise, and instructing the subject in a similar way as in our experiment. The blowing pressure and sound output signals would be recorded and processed, providing more realistic data. It would also be of interest to compare a group of professionals with a matched group of amateur and novice players, in order to investigate the possible effects of training on pressure sensation.

Conclusions

The factors that are involved in the perception of blowing pressure are complex and not easily isolated from each other, as the internal pressures are produced and sensed by different organs and mechanisms. Even so, our psychophysical approach seemed to yield reproducible and consistent data with highly trained musical subjects. The relationship between stimulus and perception, as established by our production method, was quasi-linear in almost all cases, while the power function regression still kept acceptable goodness of fit, with exponents in average close to one. This also suggests that sensation of blowing pressure, which exponents reach comparatively high values, provides important clues for the musician's control of the instrument. The power function exponents in most subjects were positively correlated to lung volume. Estimation of the difference threshold, a relevant parameter for quantifying sensation, is not available through this method and should be provided by alternative methods, such as cross-modality comparisons. Considerable inter-individual differences in estimated sensitivity indicate that average values are not adequate to predict the behaviour of subjects in general terms. We used a limited group of subjects, all of them players of reed woodwinds. We plan to include more subjects and representatives of other wind instruments in future investigation. Psychophysical methods seem useful for assessment of playing abilities in players, and possibly for evaluating specific training programs designed to improve respiratory control in performance.

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Appendix

Table 2 **.***All valid sequences performed by the eight subjects at lung volume levels V1, V2 and V3. The initial, minimal and maximal pressures produced are shown in the columns (pressures in cmH_2O), separated by "/" . When the minimum pressures equal the initial pressures, the values are shown just once. The values for the power function exponent, PFE, see Eq.2, are also shown for each trial and their mean value presented in column on the right.*

subject	**volume**	**trial1**			**trial2**			**trial3**			**volume**	**PFE mean**
		sequence	pressures	PFE	sequence	pressures	PFE	sequence	pressures	PFE		
1	V_1	121241241	17/ 16.5/ 56.5	1.29	12124242	8/ 37	0.83	124241241	11/ 9.5/ 49	0.90	V_1	**1.00**
	V_2	12121241421	12/ 46	1.18	1242121421	11.5/ 47.5	1.10	1242121421	11/ 9.5/ 35.5	1.12	V_2	**1.13**
	V_3	1241412412	18/ 17.5/ 88.5	0.98	1241214121	18/ 60.5	1.30	1412142124121	21.5/ 17.5/ 84	1.10	V_3	**1.13**
2	V_1	121212	6/ 3.5/ 27	0.46	124124121	7/ 3.5/ 91	0.45	121412141	12.5/ 3.5/ 95	0.44	V_1	**0.45**
	V_2	1212414	15.5/ 7/ 84.5	0.64	12412124121	8.5/ 3.5/ 90.5	0.38	121412421	13/ 1.5/ 69.5	0.35	V_2	**0.46**
	V_3	1212121241	27.5/ 14.5/ 47.5	0.80	1212414121	30.5/ 12.5/ 99.5	0.54	124124214121	32/ 13.5/ 100.5	0.79	V_3	**0.71**
3	V_1	121242121421	9.5/ 8/ 27	1.09	121214124121	13.5/ 11/ 44	1.01	121214124121	14/ 11/ 45.5	0.97	V_1	**1.02**
	V_2	12421212412	17/ 8.5/ 62.5	0.64	1242421421	17.5/ 14.5/ 52	1.13	124124141214	20/ 11.5/ 54.5	0.89	V_2	**0.89**
	V_3	12124121241	22.5/ 12/ 68.5	0.83	12121421241	24.5/ 13.5/ 61	0.93	124212412141	25/ 16/ 74.5	0.96	V_3	**0.91**
4	V_1	121212	7.5/ 4.5/ 21.5	0.49	124241	9/ 7.5/ 44	0.82	12124142	8.5/ 8/ 50.5	0.71	V_1	**0.67**
	V_2	1212121	10.5/ 7.5/ 27.5	0.60	12414121	9.5/ 9/ 59	0.73	124141421	11/ 6.5/ 52.5	0.69	V_2	**0.67**
	V_3	1212121	19/ 14.5/ 31.5	0.91	124124121	13.5/ 11.5/ 67.5	0.84	124142421	15/ 58.5	1.10	V_3	**0.95**
5	V_1	12124142	2.5/ 2.5/ 25.5	0.55	1242421	2/ 28.5	0.50	124241	2/ 29	0.48	V_1	**0.51**
	V_2	1214121421	12.5/ 12/ 27.5	1.41	14124241	13.5/ 12/ 38.5	1.31	12414121	12.5/ 36.5	1.35	V_2	**1.36**
	V_3	12121212	22.5/ 32	2.32	1212414121	23/ 49.5	2.09	12124141241	22.5/ 60.5	1.79	V_3	**2.06**
6	V_1	1241	12.5/ 7/ 55	0.71	1212412	15.5/ 11.5/ 68.5	0.69	121212	15.5/ 29	1.18	V_1	**0.86**
	V_2	1212121	19.5/ 19/ 42	0.88	121241241	19/ 16/ 83.5	0.92	1412121412	20/ 19/ 92.5	0.87	V_2	**0.89**
	V_3	124121	35/ 31/ 99.5	1.24	1212141212	33/ 31/ 102	1.24	12124141212	33/ 31/ 102.5	1.17	V_3	**1.22**
7	V_1	1212412	8.5/ 7.5/ 26	0.94	124124	7.5/ 26.5	1.22	124124	8/ 32.5	1.12	V_1	**1.09**
	V_2	1241241	9/ 34.5	1.00	12412141	7.5/ 35	1.14	1241241	7/ 35	1.00	V_2	**1.05**
	V_3	124124	13.5/ 37	1.47	1241242	14/ 35.5	1.39	1214241	13.5/ 12.5/ 37	1.24	V_3	**1.37**
8	V_1	1212121	6.5/ 4/ 15.5	0.60	12421	8/ 27.5	1.09	12421412	4.5/ 2.5/ 38	0.57	V_1	**0.76**
	V_2	1212121421	8.5/ 6/ 41.5	0.66	124124241	8.5/ 7/ 42.5	0.85	121421212	8.5/ 6/ 38	0.76	V_2	**0.76**
	V_3	1212421	10.5/ 2.5/ 40	0.47	121141212421	7.5/ 41.5	0.82	124212141	7.5/ 43	0.87	V_3	**0.72**

Table 3. Average values of r^2 (determination coefficient) for the subjects' data at each of the three lung volumes, and according to the four models, see Eqs. 1 to 4.

subject	V	linear	power	log	exp
1	1	0.971	0.972	0.954	0.910
	2	0.968	0.965	0.969	0.889
	3	0.933	0.954	0.952	0.878
2	1	0.882	0.888	0.827	0.867
	2	0.947	0.859	0.747	0.954
	3	0.946	0.856	0.799	0.913
3	1	0.938	0.952	0.850	0.974
	2	0.903	0.878	0.765	0.958
	3	0.870	0.872	0.791	0.889
4	1	0.986	0.968	0.915	0.979
	2	0.968	0.943	0.890	0.981
	3	0.969	0.941	0.901	0.959
5	1	0.967	0.924	0.794	0.980
	2	0.984	0.964	0.981	0.926
	3	0.954	0.922	0.935	0.920
6	1	0.943	0.908	0.890	0.903
	2	0.989	0.987	0.957	0.921
	3	0.981	0.975	0.951	0.927
7	1	0.872	0.916	0.807	0.925
	2	0.945	0.923	0.847	0.972
	3	0.918	0.951	0.857	0.968
8	1	0.971	0.954	0.883	0.979
	2	0.937	0.892	0.847	0.873
	3	0.891	0.815	0.746	0.869

Table 4. Respiratory profile, as obtained during respiratory manoeuvres through a calibrated pneumotachograph, and additional data about the subjects

Subject	Instrument	IC[liters]	VC[liters]	Height [m]	Age [years]	Gender	weight [kg]
1	Oboe	4.6	5.9	1.85	41	M	86
2	Oboe	4.2	6	1.82	38	M	82
3	Clarinet	3.2	5.2	1.85	35	M	89
4	Clarinet	2.1	2.9	1.6	32	F	57
5	Saxophone	3.7	4.8	1.79	48	M	96
6	Saxophone	3.4	4.8	1.78	31	M	90
7	Bassoon	3.4	4.9	1.78	37	M	70
8	Bassoon	3.5	5.5	1.91	52	M	86

A self-sustained vocal-ventricular phonation mode: acoustical, aerodynamic and glottographic evidences

Leonardo Fuks[1], Britta Hammarberg[2] and Johan Sundberg

Abstract

This investigation describes various characteristics of a particular phonation mode, vocal-ventricular mode (VVM), as produced by a healthy, musically-trained subject. This phonation mode was judged as perceptually identical to that used in the Tibetan chant tradition. VVM covered a range close to an octave, starting at about 50 Hz. High-speed glottography revealed that the ventricular folds oscillated at half the frequency of the vocal folds thus yielding a frequency of $f_0/2$*. Phonation at* $f_0/3$ *was also possible. Presumably, aerodynamic forces produced by the glottal flow pulses sustained the vibrations of the ventricular folds. Complementary aspects of this type of phonation were compared to phonation in modal and pulse registers by acoustical analysis of the audio signal, by inverse filtering of the flow signal and by electroglottography (EGG). In addition, oesophageal pressures were measured. These analyses revealed that every second flow pulse was attenuated because of the ventricular fold vibrations and that the laryngeal contact area alternated between two minimum values. The spectra of VVM sounds contained clear harmonic partials up to about 4 kHz. Oesophageal pressure tended to change when phonation switched between VVM and modal phonation. Examples of periodic pulse register, another case of voice period multiplication, produced patterns of EGG waveform differing from those of VVM. The possibilities of using VVM in contemporary music, whether in a purely vocal form or during to wind instrument playing, are discussed.*

Introduction

In certain types of voice pathology the ventricular folds (Figure 1) vibrate (Freud, 1962; Boone, 1983; Titze, 1994). According to Titze (1994), such vibrations also occur in vocal effects used in some pop singing; for instance, it has been assumed that Louis Armstrong used the ventricular folds in singing. It has been reported that the false vocal folds may adduct more than the true ones, vibrating independently and in other cases are adducted together, establishing a complicated vibration pattern. In cases of pathological phonation, the ventricular oscillations are often non-periodic. However, periodic oscillation has been documented in patients with ventricular dysphonia, e.g. by Nasri and co-workers (1996). In trained classical western singers, on the other hand, the ventricular folds are described to flatten against the lateral wall of the larynx (Pressman & Kelemen, 1955). Studying Tuvanian performers of overtone singing by means of x-ray photography, Dmitriev et al. (1983) observed a close approximation of the ventricular folds. Lindestad and co-workers (1998) have recently reported simultaneous oscillations of the ventricular and vocal folds, observed by high-speed glottography, on a trained subject singing in the Mongolian style.

Ventricular oscillations generally occur at lower frequencies than those normally observed in the vocal folds. However, other types of phonation may also present low frequencies without necessarily involving ventricular fold activity. Pulse register refers to a mode of phonation with a pulse-like vibratory pattern (Hollien, 1974). It is generated in the glottis and sometimes also referred to as vocal fry, glottal fry, creak, creaky voice and Strohbass. Pulse register does not even need to be periodic. Regarding Strohbass, used in some ethnical types of music (e.g., “Don-Cossack”singing),

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[1] UFRJ- Rio de Janeiro Federal University-School of Music, Rua do Passeio 98, 20021-290, Brazil

[2] Also at Karolinska Institute, Dept. of Logopedics and Phoniatrics, Huddinge Univ. Hosp., SE-14186, Huddinge, Sweden

regularity is probably mandatory. A periodic pulse register may sound lower than 20 Hz in some cases.

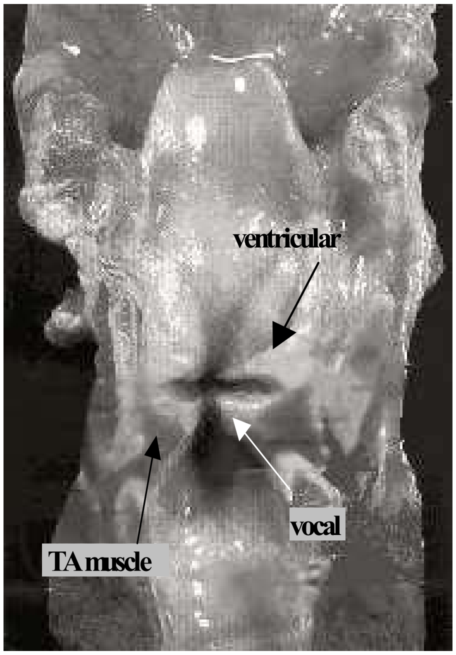

Figure 1. A coronal section through a dissected larynx, showing the vocal and ventricular folds and the thyroarythenoid muscle (TA), which includes the vocalis muscle. The configuration in this picture should be close to that during vocal-ventricular phonation. Photo adapted from Rohen & Yokochi (1993).

The abundant citation of ventricular fold vibration in some types of phonation still seems to be lacking a comprehensive theory, and experimental data are apparently scarce. The aim of the present investigation was to apply a combination of presently available analysis techniques to periodic ventricular fold phonation in order to elucidate how such vibrations are generated. Also, this kind of phonation was compared to pulse and modal register phonation.

Materials and methods

The subject, co-author LF, is a professional wind-instrument musician and acoustician at the age of 36 years who also has experience in several extended vocal techniques (Barnett, 1977). The subject phonated with a particular voice effect that appeared related to ventricular fold vibration. Preliminary laryngeal video-stroboscopy had been performed under similar conditions, indicating simultaneous vibration of the vocal folds and the ventricular folds. However, the degree of resolution and the frame rate achieved did not allow for information on phase relationships and more detailed representation of the whole cycle. The subject sustained a low-pitched tone (Bb$_1$, approx. 58 Hz) on the vowel /♋/. The Bb$_1$ was chosen due to the fact that it was rather comfortable to produce and offered a SPL range of approximately 64 dB (with closed mouth) to 88 dBA at 0.3 m distance. Any vowel could be produced within the range G$_1$ to F#$_2$, approximately. The sound was generally initiated one octave higher (Bb$_2$) and then suddenly switched to the lower frequency.

In addition to the steady tones, the subject used an overtone-singing technique on the same effect, producing the melody of “Oh Susanah” on a fixed fundamental frequency of 53 Hz, approximately. Also, the subject produced examples of periodic pulse register, alternating with modal register at the pitches of C#$_3$ (138 Hz) and G#$_3$ (207 Hz). The pulse register also produced the perceived pitches of $f_0/2$ and $f_0/3$, for C#$_3$ and G#$_3$, respectively. These examples were recorded in the same way as described below, with the exception of high-speed photography and inverse-filtering.

Audio, videolaryngo-stroboscopic, high-speed video imaging, electroglottographic and sub-glottal pressure recordings were performed. A Speedcam+ high-speed camera (Weinberger AG) with a resolution of 256x64 dpi was employed for obtaining the high-speed glottograms (Eysholdt et al., 1994). The recording was carried out at the Huddinge Hospital, department of logopedics and phoniatrics. The frame rate was 1904 per second, and each take lasted for approximately one second. The sequence and the audio signals were digitally stored on a PC and also on a video tape. For laryngoscopy, a rigid telescope (70° Hopkins 8706 CJ, Karl Storz) with a light source (Olympus Xenon, type CLV-U20) was employed. Several takes were recorded and stored.

On a different occasion, the transglottal airflow during this type of phonation was analysed by inverse-filtering (Rothenberg, 1973). The flow signal was captured by a Rothenberg mask, while the subject sustained the same pitch and vowel as during the video-recorded session. Flow calibration was performed at 400 and 1200 l/h, obtained from an air bottle attached to a flow meter. The audio signals were captured by the microphone of a sound-level meter (Ono Sokki LA-210) that was placed at 1 m distance, the output of which also contained the SPL readings. The recordings were performed in a sound-treated room.

Electroglottography (EGG) was simultaneously accomplished by attaching the electrodes (Glottal Enterprises type SC-1B) over the thyroid cartilage area (Fabre, 1957; Orlikoff, 1998). All the above-mentioned signals were directly recorded into a PC computer, through a DT- 2821 Data Translation board.

Subglottal pressures during alternation between modal voice and the particular phonatory effect considered were indirectly measured by a thin pressure transducer (Gaeltec CTO-2 strain gauge catheter, 2 mm diameter; Gaeltec S7b amplifier) introduced through the nose and placed at approximately 4-6 cm below the upper oesophageal sphincter. Those pressure signals were calibrated against a standard manometer connected to the mouth, while the subject produced three levels of static pulmonary pressures: 0, 20 and 40 cm H_2O (Fry et al., 1952).

All data were recorded as files under the SMP format, using SoundSwell program with a sampling frequency of 16 kHz per channel. For data processing comprising amplification, post-calibration, filtering, spectral analysis and display of data, SoundSwell and Extract (Nyvalla DSP, Stockholm) software packages were used.

Subjective expert evaluation

The subject demonstrated these voice effects to a Tibetan Buddhist, who had spent his life up to mature age in a Tibetan community, and asked him to judge how similar these effects were to the traditional voice produced by certain Buddhist monks. The expert also judged the pulse register voice, produced at the same pitch as before. Examples of these two types of phonation were demonstrated in quasi-random order. He found the first one practically identical to that used by Tibetan monks, while he considered the pulse register voice as "slightly similar but not as loud and deep as the typical Tibetan sound".

Analysis and results

High-speed imaging

In all recordings, the high-speed video film showed a similar and regular pattern, revealing that the ventricular folds closed symmetrically at every second cycle of the vocal folds. This oscillation mode will henceforth be referred to as the *vocal-ventricular mode* (VVM). A short sequence, comprising about 3 cycles was converted from the videotape into a digital MPEG-compressed format, by means of a Silicon Graphics O2 workstation and using Media Recorder program. Then, 18 equally-spaced frames of a complete cycle, corresponding to approx. 17.2 milliseconds were captured. This sequence of frames is shown in Figure 2. The indicated angles refer to the 40 degrees angular steps relative to f_0, 116 Hz.

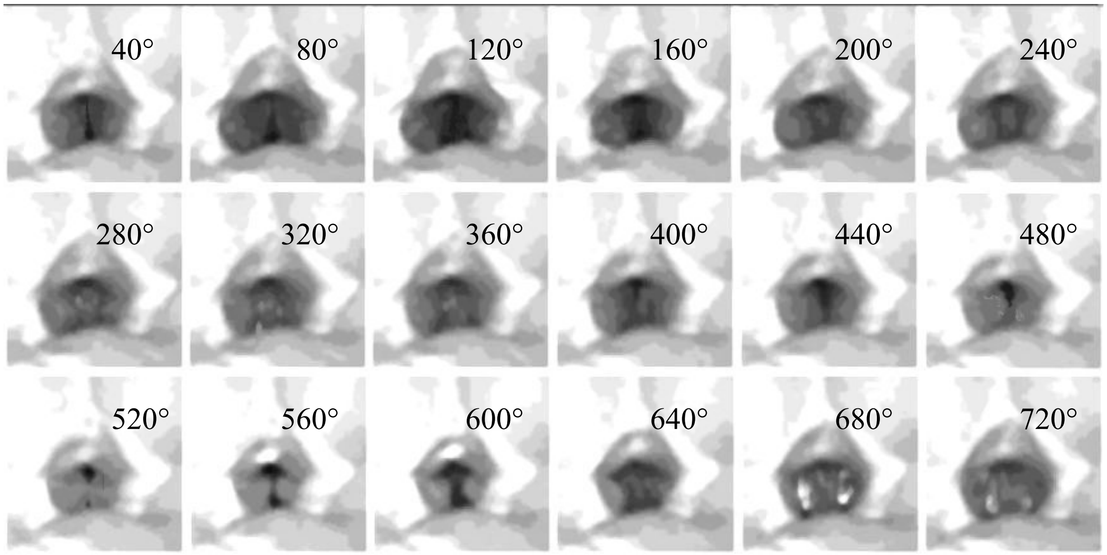

Figure 2. A complete cycle of the vocal-ventricular mode (VVM), obtained from high-speed glottography at 1904 frames/sec. Fundamental frequency of the vocal folds is 116 Hz and the ventricular folds oscillate at 58 Hz. The first cycle is purely vocal (0°-360°), while the second cycle is affected by the ventricular closure, during the 480°-560° interval, when the vocal folds were open. Ventricular folds appear as a pair of round and light-tone protuberances. Duration of the whole sequence is 17.2 milliseconds, approximately.

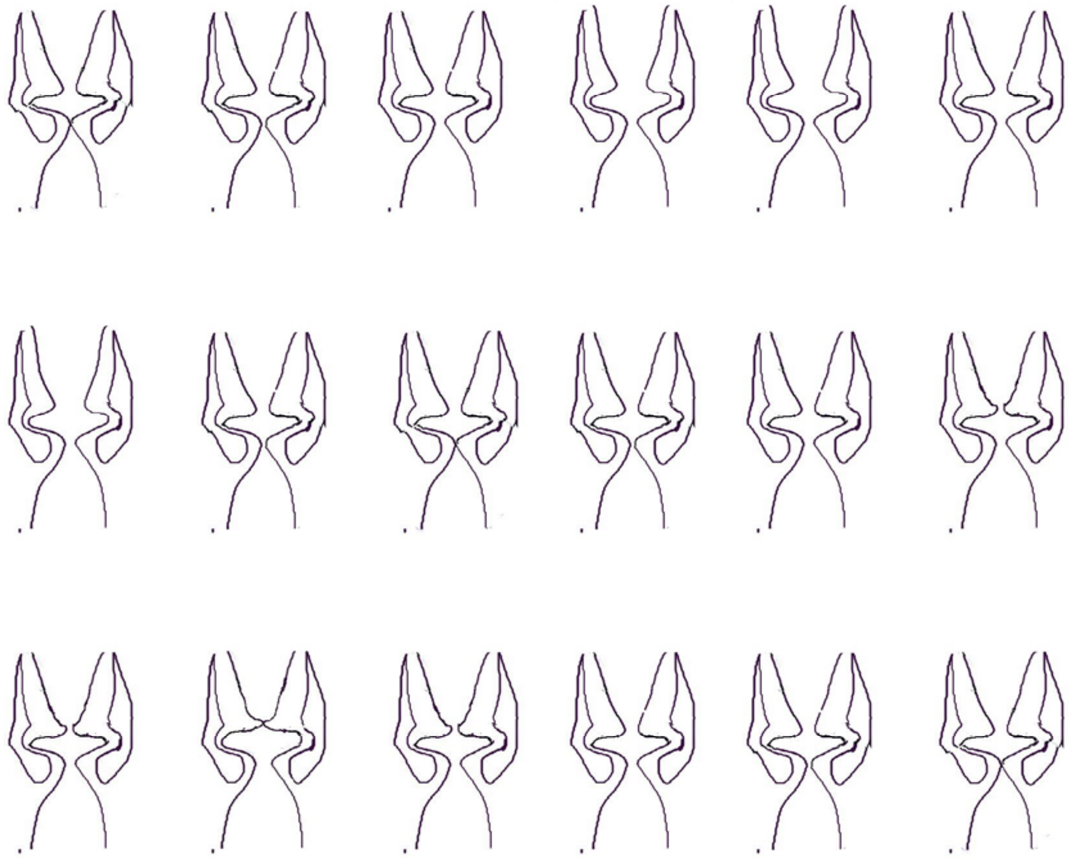

Figure 3. Sequential diagram of a whole $f_0/2$ vocal-ventricular cycle in coronal section, starting from closed glottis, see Fig. 2. Each frame corresponds to a 40^o angular step relative to f_0 (116 Hz).

The images provided by the high-speed video recording display a superior view of the glottis. An attempt to construct a sequential diagram of the larynx in coronal view was done on the basis of the sequence shown in Figure 2. Figure 3 shows the result in terms of a schematic interpretation of the shapes of the folds and the distances between the structures. To gain more detailed information other imaging techniques need to be recruited.

Comparing modal register to vocal-ventricular mode (VVM)

Figures 4 and 5 show simultaneous audio waveform, flow glottogram (FG), electroglottogram (EGG) and power spectrum of modal voice and its corresponding VVM, respectively. As compared to Figure 4, presenting a sequence of four cycles of the audio signal, the second and fourth cycles in Figure 5 are damped to approximately one third of the amplitude, i.e. -10 dB. The corresponding pulses of the FG signal were even more damped, -13 dB approx. The duration between the pulse peak and the intersection with the baseline for the FG curves, i.e. the duration of the closing phase, was estimated from a series of eight consecutive cycles. Modal voice showed a longer closing duration (1.63 ms) than the VVM (1.50 ms). Furthermore, the amplitude of the flow pulse for the modal voice was considerably lower (Figures 4 and 5). This means that in VVM the descending part of the FG curves was significantly steeper. As a consequence, its spectrum can be expected to contain more energy for the higher partials. For a more profound analysis of the FG signals, a time derivative of the glottal flow curves should be obtained and the parameters which describe the waveshape calculated. To quantitatively predict the impact of these differences on

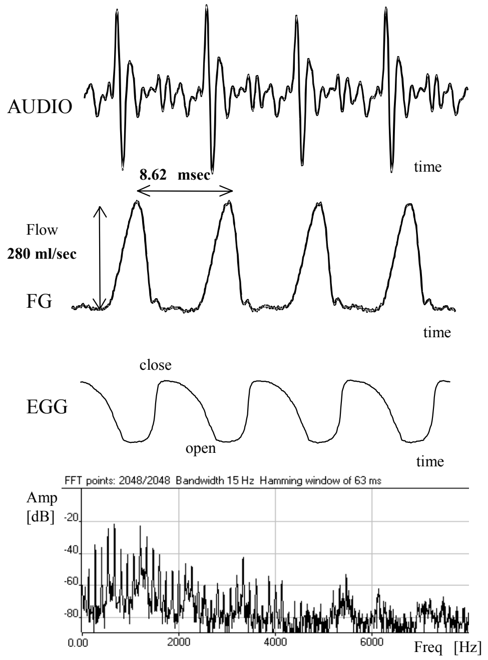

*Figure 4. Audio, Inverse-filtered (FG), EGG and power spectrum representations of an /ɑ/ vowel, **modal register,** at 116 Hz (Bb$_2$). The EGG waveform shows a constant peak-to-peak pattern.*

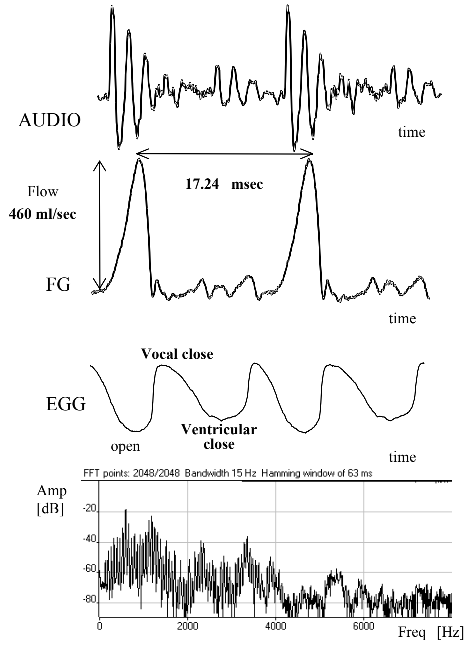

*Figure 5. Audio, Inverse-filtered signal (FG), EGG and power spectrum representation of an /ɑ/ vowel, **VVM**, vocal folds at 116 Hz (Bb$_2$); ventricular folds at 58 Hz (Bb$_1$). EGG signals peak at consistent values at every semi-cycle, but alternate in lower values between open glottis and closed ventricular folds.*

formant levels the LF-model of glottal flow (Fant et al., 1985; Fant, 1997) can be applied.

The EGG signal (Figure 5) illustrates the degree of glottal contact area. The flat baseline appearing in Figure 4 (high impedance-open glottis), cannot be seen, but rather an alternation between a higher and a lower position of the valleys reflecting an alternation between two degrees of contact. The somewhat higher conductance of the larynx occurs precisely when the ventricular folds meet at every second cycle between two closures of the vocal folds. The peaks, corresponding to vocal fold closure, are similar in amplitude.

The spectra of the audio signals in Figures 4 and 5 have similar envelopes, since the same vowel was produced in both cases. Both show a harmonic spectrum, although the density of the partials for the VVM tone is twice that of the modal. However, the VVM phonation exhibits more energy between 2 kHz and 6 kHz than the modal. Figure 6 displays the same spectra in the range 0-1 kHz. In the VVM spectrum, the 58 Hz "undertone" is considerably weaker than the 116 Hz partial; generally a difference of 6 to 10 dB was observed. In the spectrum of the FG signal for VVM the 58 Hz component was as strong as the 116 Hz component. This result was expected since the vocal tract transfer function increases with frequency up to the first formant. Still, the 58 Hz tone was perceptually quite salient (Moore, 1997).

Overtone singing with VVM source

Figure 7 shows a spectrogram in the range 0-4 kHz for "overtone singing" of the melody "Oh, Susanah", as performed by the same subject while keeping a constant f_0. The first formant remains at approximately 400 Hz while the melody ranges between 800-1400 Hz (partials #16-26). Two other simultaneous overtone patterns, somewhat mirroring the melody, can be seen, one between 1700-2200 Hz (partials #32-42) and the other between 3000-3500 Hz (partials #57-66). The top formant seems equivalent to a "speaker's formant" (Sundberg, 1974; Leino, 1994). The inverted melodic movement suggests that in this particular overtone technique, the tongue constriction separates the mouth into two resonant cavities. A movement of the constriction produces a volume reduction in one compartment and a volume increase in the other.

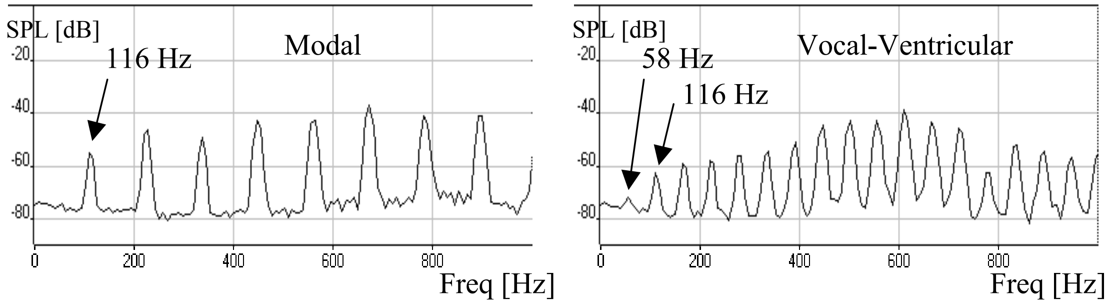

Figure 6. Detail of spectra (range 0-1000 Hz) from modal and VVM examples as in Figures 4 and 5. In the VVM spectrum, the 58 Hz "undertone" is considerably weaker than the 116 Hz partial, in general a difference of 6 to 10 dB as observed in our samples. All other harmonics of 58 Hz are present throughout the spectrum.

Fo/3 Ventricular oscillations

By laryngeal adjustment and by choosing a higher f_0, the subject was able to flip to a pitch that was a duodecime (19 semitones) below the starting pitch. Figure 8 shows the audio signal, its spectrum and the EGG recording for a typical example produced on the vowel /□/ at an f_0 of 176 Hz (F3). The audio and EGG signals are complex but periodic. In each cycle, the EGG waveform indicates short instances of maximal glottal opening interspersed with two apparently incomplete openings, i.e., reflecting an intermediate degree of glottal tissue contact. The spectrum contains multiples of 59 Hz, approximately, starting from 176 Hz. Thus, the 59 Hz and 116 Hz components are missing. Perceptually, this signal sounds as having the same pitch as the one shown in Figure 5, Bb_1 (59 Hz), although with a different tone quality. Interestingly, the sub-cycles (the peaks in the EGG waveform) indicate a quasi-periodic jitter. Unfortunately, the subject could not produce this type of phonation with the rigid telescope, so no high-speed imaging could be made.

Pulse register

Examples of this type of phonation showed a high degree of regularity. Phonation started in a steady modal tone which then suddenly switched into $f_0/2$ (Figure 9) or $f_0/3$ (Figure 10). For the example shown in Figure 9, the initial f_0 was a C$\#_3$ (approx. 138 Hz) and the period-

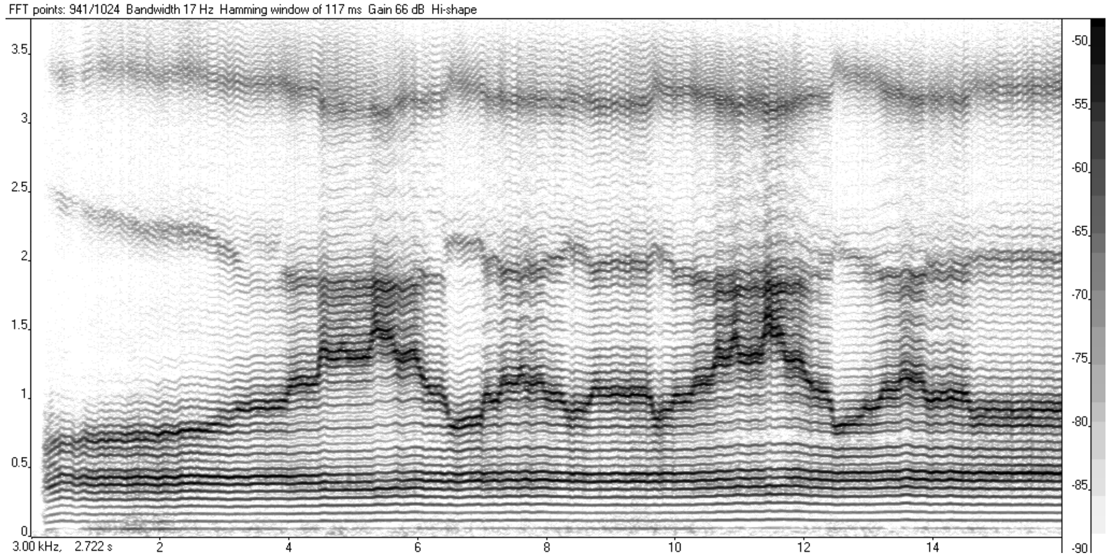

*Figure 7. Overtone singing ("Oh, Susanah" melody) spectrogram from a **VVM** utterance, at a rather fixed ventricular frequency, approx. 53 Hz, produced by the same subject.*

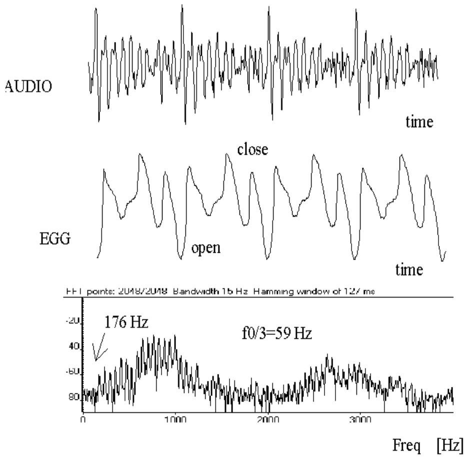

Figure 8. VVM f_0/3 example: waveform, EGG and power spectrum. Vocal folds at 176 Hz; ventricular folds presumably at 59 Hz.

doubling yielded an audio signal containing multiples of 69 Hz, starting from 138 Hz. For the example in Figure 10, the voice started at 207 Hz (G#$_3$) and again the transition resulted in 69 Hz modulating frequency (f_0/3), the spectrum containing multiples of 69 Hz that started from 138 Hz. Both these examples were perceived as having the same pitch, but different sound qualities. The highest sound power that could be produced was considerably lower in the pulse register than in the VVM. The EGG shows striking differences if compared to Figures 5 and 8, although still revealing the origin from a multiplication of the period time by 2 or 3.

Oesophageal pressures

While repeatedly alternating between modal and f_0/2 VVM, starting on Bb$_2$ (116 Hz) in modal register, the subject tried to keep a constant SPL of 79 dBA @ 1 m (SD = 1.0) for the modal tone. The subject also tried to constantly produce a loud VVM tone, resulting in an SPL of about 84 dBA. For the phonations in modal register, the average oesophageal pressure was 18.0 cm H_2O (SD = 0.6) while for the VVM, it was 21.9 cm H_2O (SD =1.0) These averages were calculated from four consecutive transitions.

These pressures are rather high as compared to the ones used in normal phonation or even in singing (Van den Berg, 1956; Cleveland & Sundberg, 1985). Apparently, an initially pressed voice was used in the modal register, which seemed necessary for the subject in order to facilitate well controlled and sudden transitions.

Discussion

The data presented in this report refers to a single healthy subject using three different phonation modes, modal, vocal-ventricular and pulse register. Obviously, inter-individual and even intra-individual variations can be expected. Yet, it seems likely that similar observations would emerge from studies of other subjects

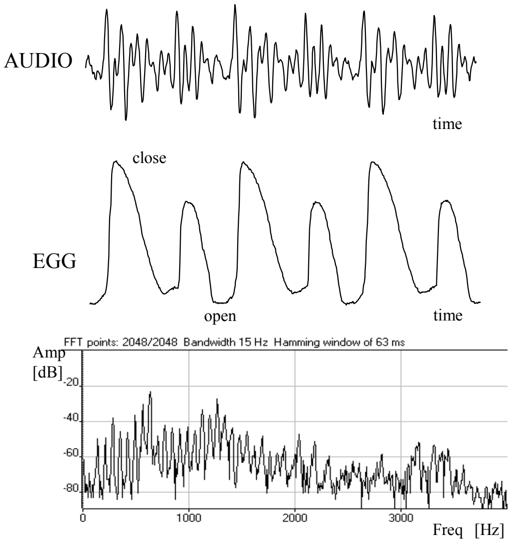

Figure 9. f_0/2 Pulse register (Strohbass), starting at C#$_3$ (138 Hz) and switched to C#$_2$ (69 Hz). Notice the difference in EGG pattern respect to Figure 5.

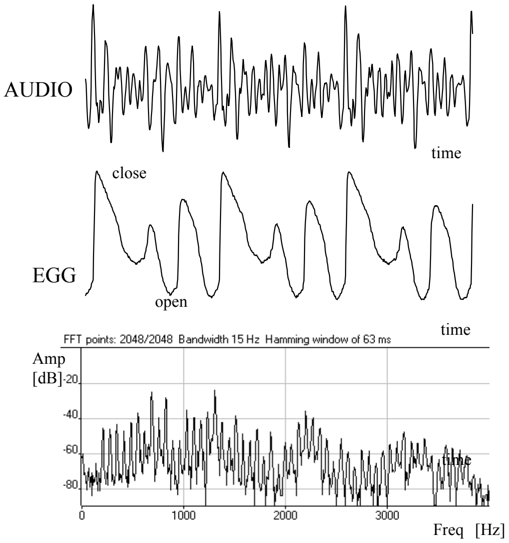

Figure 10. f_0/3 Pulse Register (Strohbass), starting at G#$_3$ (207 Hz) and switched to C#$_2$ (69 Hz). Compare the EGG signal with Figure 8.

producing the same types of phonation. On the other hand, ventricular dysphonia may be characterised by other laryngeal configurations, since the organic and functional prerequisites may differ from a normal subject. The advantage of focusing on these particular steady and self-sustained effects is that they provide a more robust platform to examine mechanisms which otherwise would present higher instability and transient states.

The subject is an adult male, age 36. It is an interesting issue whether the ability of producing VVM is related to gender and/or age. It has been reported that a female professional singer was capable of such phonation at 130/65 Hz (Barnett, 1977). The observed lack of female singers performing such effects in ethnical music recordings may be simply due to tradition.

Regarding vocal health, the subject never experienced any voice problems even after extensive use of the VVM. Still, attention is of course recommended to those who use all kinds of extended vocal techniques.

Period multiplication

Chaos theory has been found a useful tool in describing phenomena associated with complex vocal fold vibration (e.g., Berry et al., 1994; Davis & Fletcher, 1996). Bifurcations and chaos have been identified in the cries of newborns (Herzel & Reuter, 1996) and in asymmetric vocal fold oscillations (Steinecke & Herzel, 1995). It would be worthwhile in future research to apply chaos theory also to VVM.

Period multiplication, e.g., $f_0/2$ or $f_0/3$, occurs also in pulse register phonation (Barnett, 1977; Titze, 1994). This register has been studied and described by several authors (e.g. Hollien, 1974; Titze, 1994; Keidar, 1986; Blomgren & Chen, 1998). However, accurate measurements of the degree of vocal fold adduction, stiffness of the vocal fold margins and their precise movement are still required for a complete understanding. Investigation of the role of the ventricular folds in the pulse register mechanism has been proposed by Blomgren & Chen (1998).

The EGG waveform patterns were found to clearly differ between VVM and pulse register. In VVM the vocal and ventricular folds apparently closed in opposite phase, while in the pulse register EGG no indication of such opposite phase vibration could be observed. It would be interesting to apply physical modelling to both VVM and pulse register.

Vocal "growl" seems to be a related vocal effect that is sometimes used by jazz and pop musical singers, e.g., Louis Armstrong. Phonation is usually breathy, complemented by a constriction of pharyngeal/laryngeal structures, as revealed by video-stroboscopy (Thalén M, personal communication). This supraglottal valve mechanism produces a modulation of the airflow, and hence of the sound quality, adding irregular or regular oscillations at low rates to the sound. In some cases, the "growl" vibrations may present a phase lock to the vocal folds in the $f_0/2$ or $f_0/3$ modes. Spectral analysis of some of Armstrong's recordings did not show similarity with our VVM examples, although some subharmonics were observed.

Terminology

A vocal tradition in different regions in Central Asia such as Tibet, Tuva, Mongolia and Ladakh have been reported to include very low pitched drones, often complemented by shifting, salient high pitched partials (Zemp, 1996; Bretèque, 1988; Bloothhooft, 1992). The same or similar effects have been referred to by many other terms, including overtone or diphonic singing (Smith et al., 1967), or "dyplophony" (Dmitriev, 1983), "throat-singing", etc. A curious and somewhat humorous variant is the voice of the cartoon character *Popeye*, who had a very low-pitched and harsh voice (down to Bb_1, 58 Hz, during singing), possibly produced by VVM. A thorough analysis of the kind applied in the present investigation would be needed for an exhaustive description of the phonatory characteristics of these tone production modes. A coherent terminology should be based on the results of such analyses.

Towards a physical model for VVM

The vibrational mechanism of the vocal folds can be represented by models, such as the classic two-mass model (Ishizaka & Flanagan, 1972), the partial differential equations models (e.g. Titze & Talkin, 1979), the multiple coupled oscillators model (Story & Titze, 1994) and the simplified two-mass model (Steinecke & Herzel, 1995). All these models imply that adjacent oscillators in the vocal folds are mechanically linked by springs, as in the lower part of Figure 11. In the case of VVM, it seems inadequate to represent the anatomically distant oscillators as adjacent, as they are separated by the laryngeal ventricle. The comparatively flaccid structure of the ventricular folds and the motional configuration indicated by the high-speed glottograms, suggest that they close because of the negative pressure generated during the open phase of the vocal folds. This force is probably strong enough to produce the collision in a "superior glottis" that is skilfully shaped by the subject. Therefore, the mastering of the VVM technique may involve the simultaneous control of adduction and positioning both at the glottal and the ventricular levels, thus generating self-sustained oscillations.

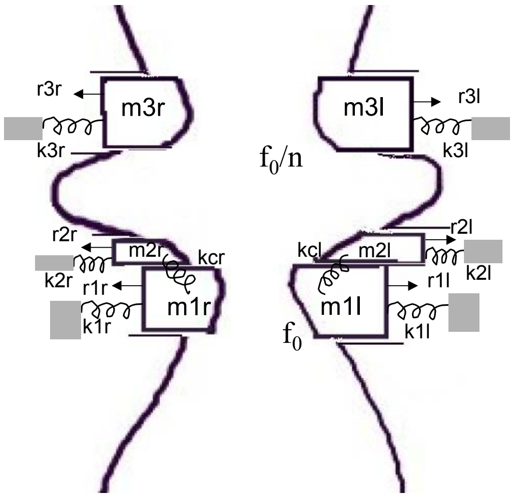

Figure 11. A proposed model for the VVM mechanism. The lower part, referring to the vocal folds, is a simplified two-mass model (Steinecke and Herzel, 1995), while the upper part consists of a pair of single masses excited by the aerodynamical forces. The relevant elements are the masses (m), springs (stiffness k) and dampers (resistance r). Indexes r and l refer to right and left sides, respectively.

A simplification of the two-mass model is that it considers the larynx as having a bidimensional or a prismatic geometry. A real larynx has a varying mass distribution along the antero-posterior axis and asymmetries with respect to the sagittal plane (Steinecke & Herzel, 1995). These variations may be responsible for several other phonation modes that will be hard to predict by means of a simple glottal model.

In Figure 11, a model for the VVM mechanism is proposed. The lower part, the glottal system, consists of the simplified two-mass model (Steinecke & Herzel, 1995). Each component contains a mass element (m), a spring with stiffness (k) and a damper (r) absorbing mechanical energy. The two pairs of glottal masses m_{1l}-m_{1r} and m_{2l}-m_{2r} are also interconnected by a spring (kc). For simulation purposes, the coefficients m, k, and r, together with the subglottal static pressure and dimensional parameters, may be used to build a system of differential equations that can be solved and predict positions and velocities for the mass pairs (Tigges et al., 1997). The ventricular system, upper part of Figure 11, contains a couple of mass-spring elements. As seen, no mechanical links have been assumed between the glottal and ventricular systems, which, however, are aerodynamically connected. This model, which needs future implementation, would be able to oscillate within a range of frequencies, but should tend to establish a harmonic relationship with f_0, thus producing a stable, self-sustained mode. Thereby, the ventricular system will achieve the "undertone".

The natural frequency of a mass element may be roughly expressed by:

$$f_0 \approx \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad \text{Equation 1}$$

where k is the stiffness of the spring and m the oscillating mass (Figure 11). Eq. 1 does not contain any damping term and is valid for small amplitudes. For instance, during a VVM at $f_0/2$, the ventricular part can be postulated to possess a k/m ratio of approximately ¼ of the effective glottal ratio. Similarly, a VVM at $f_0/3$, the expected ventricular k/m should be approximately 1/9 of its glottal k/m equivalent.

Acoustically, these alternated closures of the vocal and ventricular folds produce different effects.

One is the partial damping of every second (or third) vocal pulse. This factor is responsible for the period multiplication and for the amplitude modulation at f_0/n.

The other effect is the increase of the effective close phase, yielding a longer period for reflection of the standing waves in the vocal tract between cycles. This results in a narrowing of the formant bandwidths, which should add to the resulting sound level and reduce the decay of the spectrum envelope.

The presence of two cascaded oscillating valves differing in phase should increase the flow resistance of the system, thus requiring higher subglottal pressures. This is in accordance with the oesophageal pressure measurements. It may be speculated that VVM phonation is facilitated at high lung volumes, since these are associated with high relaxation pressures (Agostoni & Mead, 1965); Tibetan chant, presumably produced in VVM phonation, is used for meditation.

A VVM at $f_0/1$, i.e., with the ventricular folds oscillating at the same frequency as the vocal folds, may be possible. Then, every single glottal pulse would be damped in a similar way, probably generating a highly muted sound.

Another possibility is that the ventricular folds vibrate at a multiple of the vocal frequency, i.e. n x f_0. In this case, the ventricular folds would serve as the main oscillator. These speculations call for additional experimental data and further investigation.

Vocal registers

The above findings raise the question whether or not VVM should be regarded as a special vocal register. Unfortunately, there is no general agreement on vocal register terminology. According to Hollien (1974), there are no more than three registers (a) loft, also referred to as falsetto; (b) modal or chest register; and (c) pulse register, also called vocal fry, creaky voice or, in singing, strohbass. From our observations, the VVM phonation does not seem similar to any of the above registers. Thus, it appears reasonable to accept it as a register of its own.

Musical implications

Some contemporary music makes use of special vocal techniques adding new sonorities to the available resources. We have demonstrated that the VVM is generated by a specific mechanism and can be produced at various degrees of loudness over a f_0 range of about one octave, starting from 49 Hz, approximately. These characteristics may seem attractive to some contemporary composers.

The VVM should also be applicable to the so-called “hum and play” technique, where wind instrumentalists play the instrument while vocalising. This technique is used in several wind instruments, such as brass, flute, saxophone and clarinet (e.g. Berio’s *Sequenza V* for solo trombone, William Smith’s *Variants* for solo clarinet). By changing the fingerings and lengths of the instruments, several kinds of “filters” may be defined, resulting in a gamut of new sonorities. The VVM phonation yields powerful and spectrally rich sounds, and may provide a useful extension of the present timbral possibilities.

Conclusions

This exploratory study described a particular phonatory mode produced by a healthy trained subject with simultaneous oscillations of the vocal folds and the ventricular folds.

The frequency ratio between vocal and ventricular folds was 2:1 or, in some cases, 3:1. The closure of the ventricular folds occur during the open phase of the vocal folds, thus damping every second and/or third glottal pulse. The driving of the ventricular folds seems to be a negative pressure generated by the airstream contained in the glottal pulse. A tentative model was presented to describe the mechanism. According to an expert listener, the vocal effect was similar to that produced in some monasteries of Tibet.

The subglottal pressures required were consistently higher than those used in modal and pulse register, at least in the subject used in this experiment. The pitch range approached one octave starting at 49 Hz (G_1), approximately. The SPL @ 0.3 m could be varied within 64 and 88 dBA for the 58Hz (Bb_1) tone.

This technique may appear attractive to contemporary music, and can also be employed in wind instruments playing, producing a family of new sounds.

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